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Assessment of the life expectancy and environmental performance of polylactic acid compared to cotton and polyethylene terephthalate fabrics

Umoren, Udeme

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By

Udeme Umoren

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Udeme Umoren

Phd Energy, Construction and Environment

School of Energy, Construction and Environment
Faculty of Engineering, Environment & Computing
Coventry University

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DEDICATION

To the "I am that I am"

ABSTRACT

The need to satisfy the increasing global demand for textile and clothing material due to population growth and changes in fashion trends have led to the manufacturing of short life span textiles. Current fabrics such as cotton and polyethylene terephthalate (PET) all have deep environmental impacts. This study examines Polylactic acid (PLA) fabric derived from corn as a contending replacement for cotton and polyethylene terephthalate. The use phase has been identified as the dominant contributor to environmental impacts and consequently this research has focused on how the laundry regime (wash performance) affects the life expectancy and the mechanical properties of PLA, PET and Cotton. This study excludes daily wear, dirt and stains.

By testing the constituent fabrics after each laundry regime, the results showed a more significant level of impact on cotton than PLA fabric in different laundry treatments with or without softener. There was no effect on PET. The load-extension behaviour showed that PLA and cotton withstood ten laundry cycles before showing any significant signs of damage; however, PET fabric retained its load-extension behaviour beyond 50 laundry cycles. From a practical standpoint, the result of this study suggests that tumble-drying should be avoided; however, the use of softeners during the laundry and air-drying seems to provide stability for PLA and PET fabrics. The influence on the cotton fabric was more from the drying process than the use or absence of softener, buttressing the fact that tumble-drying should be avoided if possible. The life expectancy of PLA fabric showed a lower lifetime (35 washes/lifecycle) compared to PET and cotton (42 and 43 washes/lifecycle respectively). With these results, a comparative lifecycle assessment was conducted during the life expectancy and after a typical school t-shirt use of 75 laundry regimes, PLA offered environmental benefits compared to PET and Cotton. The result also revealed that the environmental impact of cotton decreased by 2%, PET decreased by about 1.2% while PLA increased by 3% when the laundry lifetime was

increased to 75 wash cycles. The results obtained in this study showed that enhancing the fabric to increase its laundry lifetime does not automatically lessen the environmental impacts. Nevertheless, it has proven that even a small rise in the lifetime of PLA fabric can make it comparable and competitive with PET and cotton. In addition, the similarities in properties with PET makes PLA a valuable substitute, with a sustainable low environmental burden. In comparison to cotton (Energy Demand 36.5%, Water Consumption 53%, and Global warming potential Contribution 43%), PLA (Energy Demand 28.5%, Water Consumption 21% and Global warming potential Contribution 22%), demonstrates a better alternative in all aspects and is recommended as a suitable replacement due to its potentially low water and energy use, and CO_2 emission.

Key Words:

Renewable Resource; Biodegradable; Polylactic Acid; Polylactide; Fibre: Textile: Clothing: Experiments: Fabrics: Modelling: Life Cycle Assessment; Fabric Life Expectancy

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LIST OF SYMBOLS/ABBREVIATIONS

%E	Tensile Extension
A	Cross sectional area,
b	width of the specimen
C	Carbon
CH_4	Methane
CML	Centre of Environmental Science of Leiden University
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalent
COT	Cotton
DA	Detergent and Air Drying
DSA	Detergent Fabric softener and Air Drying
DST	Detergent Fabric softener and Tumble Drying
DT	Detergent and Tumble Drying
Ex	Extension
F	max load reached
g	gram
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP100	100-year Global Warming Potential
H	Hydrogen
H_2O	Water
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
J	Joules
kWh	kilowatt-hour
L	Gauge length of the specimen
LCA	Life Cycle Assessment
LCI	Lifecycle Inventory
LCIA	Lifecycle Impact Assessment
MJ	Megajoules
MPa	Mega Pascal
MWh	Megawatt-hour
N	Newton
N_2O	Nitrous oxide
O	Oxygen
PED	Potential energy demand
PET	Polyethylene Terephthalate
PLA	Polylactic acid

S	Sulphur
T	Thickness of the fabric
T_g	Glass transition temperature
tkm	Ton kilometre
TWh	Terawatt-hour
X	Number of washing cycle from 0, 1, 3, 6, 10, 30, 50
ε	Strain
σ	Stress
σ	breaking strength

Conversion Factors and Energy Equivalents

1 joule (J) = 0.2388 cal

1 kilowatt-hour (kWh) = 3.6 x 10^6 J = 3.6 million Joules = approx. 860 kcal

1 cubic metre = 35.315 cubic feet = 6.2898 barrels

1 kg = 2.20462 pounds (lb)

1 cubic meter (m^3) = 1000 litre (l)

1 ha = 10 000 square meter (m^2)

1 hectare = 2.47105 acres

1 INTRODUCTION

1.1 Background

Recent decades have seen a progressive increase in the global demand for textiles and clothing materials. The main reason for this increase is the fast-growing world population, expected to reach 8.1 billion by 2025 (UNDESA 2013). Secondly, over a ten-year period (2000-2010), the global consumption of fibres increased between 8.8 to 11.6kg per capita and is forecast to reach 13.1kg per capita by 2020 (Schindler 2012). Thirdly the fast-changing fashion trends which offer a continuous stream of new clothing to the market as well as reflecting the latest and hottest design that consumers prefer at bargain prices (Choi *et al.* 2013, Joy *et al.* 2012, Schor 2005). The effect of this is the manufacturing of low-quality and short life expectancy of textiles or clothing materials (Das 2008). Further concerns are the environmental consequences associated with manufacturing cheap, low-quality materials for a fast growing and demanding world population (Niinimäki and Hassi 2011). Consumers are now showing discontent with the quality of clothing during use and maintenance and are now demanding, not just quality, but greener products as well (Niinimäki 2011, Sule 2012).

1.1.1 Environmental improvement potential from biodegradable textiles

This thesis is concerned with the fact that the demand for clothing fibres due to increasing affluence and a growing population is becoming a significant environmental problem. The current fibres from cotton, which account for 46% of all fibres, followed by polyethylene terephthalate (16%) produce significant environmental impacts during their lifecycle especially the use phase. Also, these fabrics lose some of their properties, quality, value and worth as they approaches their end of life.

During the United Nations Millennium Summit in 2000, natural fibres were identified as a potential to help meet one of the goals of reducing environmental problems (Mohanty *et al.* 2000). However, the use of natural fibre such as cotton alone to meet the world's production volume, quality and demand will compete with food crops. Also, the manufacturing of acrylic, polyester, polyamide or nylon is already an important source of environmental concern; the same scale as the production of food, water, and energy. Therefore, this research explores the potential and significance of synthetic polymer fibres such as polylactic acid (PLA) from renewable source as an alternative to cotton and polyester. So far, there has been no study to show how 100% PLA fabric would compare or compete with existing PET and cotton fabric in terms of tensile properties when subjected to the same laundry treatment or a simulation of a household domestic laundry regime.

1.1.2 Polylactic Acid (PLA)

The history of PLA dates back to 1780 when the chemist Carl Wilheim Scheel isolated "acid of milk" from sour whey (Auras *et al.* 2010). However, the earliest documentation on the polymerisation or depolymerisation of polylactic acid from lactic acid was put together in 1932 by Carothers (Linnemann *et al.* 2003). Polylactic acid (PLA) is a thermoplastic and biodegradable polymer made by the ring-opening polymerisation or polycondensation of lactic acid, lactide and lactic monomer (Bax and Müssig 2008, Rhim *et al.* 2009) as illustrated in Figure 1.1.

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Figure 1.1: Ring-opening polymerisation synthesis of Polylactide. Source: (Auras *et al.* 2010)

Lactide is prepared by the controlled depolymerisation of lactic acid obtained from the fermentation of monomers of renewable sugar-rich feedstock such as corn starch or sugar beets (Rhim *et al*. 2009). Figure 1.2 illustrates the agricultural carbon cycle, where energy from sunlight converts water and the carbon dioxide sequestrated by the feedstock into starch or additional fermentable sugar to biopolymer lactic acid.

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Figure 1.2: Carbon dioxide life cycle and sequestration through the production of Polylactic acid – NEED to put source here

The chiral nature of lactic acids allows for different stereoisomer of PLA, mainly in the L and D-form (Auras *et al.* 2011, Bax and Müssig 2008, Scott 2013). In the production of fibres, PLA is dried before melting to avoid hydrolysis, and readily forms fibres through a melt intrusion process. This process involves heating the polymer to the required melt thickness before extrusion as a fibre monofilament (Gupta *et al.* 2007). Fibres produced from PLA are as stable under normal use as other natural fibres (Blackburn 2005). PLA is similar in properties to polyethylene (PET) and polypropylene (PP) and therefore can serve as an alternative.

1.1.3 Potentials of fabric manufactured from PLA

The production of PLA fabrics is both renewable and non-polluting as well as eliminating the use of finite resources as raw materials. Identified as one of the most positive biodegradable polymers due to its mechanical property, thermoplastic, and biodegradability (Gupta *et al.* 2007),PLA is used in the manufacturing of many woven and non-woven textiles such as upholstery, disposable garments, awnings, feminine hygiene products, and nappies (Madhavan Nampoothiri *et al.* 2010). An exceptional property of PLA is its moisture management. Compared to PET or cotton, moisture spreads quicker enabling it to dry faster and be more comfortable (Auras *et al.* 2010, Ebnesajjad 2013). Also, the elastic recovery and crimp property of PLA offers an outstanding shape retention and crease resistance in garments compared to PET, (Gruber and O'Brien 2005, Lunt and Shafer 2000).

The mechanical, thermal stability, processability and low environmental impact of PLA have gained a wide range of application, for example, in the biomedical industry, packaging and agriculture (Drumright *et al.* 2000, Garlotta 2001, Rhim *et al.* 2009). The high thermal stability of PLA is an important property in many applications such as injection-moulded parts, monofilaments that require improved resistance at higher temperature and residence time in processing conditions (Murariu *et al.* 2008). Table 1.1 shows the physical properties of PLA.

Source: (Gupta *et al.* 2007)

At the end of its useful life, the fibre can be recycled back to obtain biodegradable lactic acid by hydrolysis. The lactic acid produced is reused as a monomer in the production of new PLA with the same quality, leading to a reduction in incineration (Linnemann *et al.* 2003). However, the current end of life solutions for PLA-based products is via incineration, mechanical recycling and composting (Chen 2009). PLA decomposes completely under conditions around 60^{o}C, with 90-95% relative humidity. Figure 1.3 illustrates the typical life cycle of any PLA material.

Figure 1.3: The life cycle of polylactic acid products. Source (Avinc and Khoddami 2009)

This eventually leaves the use of PLA in its original form, hence the aim of this study. The closest to this study was carried out on the mechanical properties of polylactide after repeated cleanings where yarns were extracted from PLA fabric and tested (Karst *et al.* 2008). The results of this study will add to and help inform the debate on global resource depletion and use arising from the choice of fabrics, and lead to the best fabric to choose in order to minimise resource depletion and the environmental impact of using fabrics.

The question (problem statement) is that for a 250g t-shirt made from the studied fabrics over a period of its lifetime and through several washing cycles, can PLA offer fabrics with lower environmental impacts. During the lifetime, fabrics degradation and deterioration is provoked by laundry, which is determined through tensile testing experiments on the mechanical properties. The following questions were addressed in this research:

(1) How does the impact of laundry on the PLA fabric compare with PET and cotton?

(2) What is the environmental impact associated with the use phase of PLA fabric compared to PET and cotton?

(3) What environmental impact will PLA fabric incur, when the material life expectancy was extended up to 75 wash cycles compared to PET or cotton?

1.1.4 Life Cycle Assessment

LCA is an environmental management tool use to estimate and evaluate the environmental impact of a product, process, activity, resource consumption, energy and environmental contamination of materials throughout their life cycles (Roy *et al.* 2009). These impacts, sometimes referred to as environmental footprint of a product or service, may be beneficial or adverse. It is a cradle to grave approach, involving the collection and evaluation of quantitative data on the inputs and outputs of materials, energy, and waste flows associated with a product from and to the natural environment over its entire lifetime (Rebitzer *et al.* 2004).

Typically, a life cycle impact assessment of a product is usually carried out on a cradle to grave basis. However, due to various applications of textile fabrics (such as bed sheets, carpets and rugs, and upholstery) as well as the system boundary of this study (use phase of a t-shirt Section 5.5), the impact assessment is limited to a more comparable 'cradle-to-usage'. The cradle to usage life cycle of the fabrics examined in this study is presented in Figure 1.4.

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Figure 1.4: Overview of the life cycle of the fabrics showing the different stages and phases referred to throughout the thesis. Source?

1.2 Research Aims

According to Kumar *et al* (2011), consumers have developed a throwaway attitude towards garments and apparel due to fast fashion and cheap clothing. Moreover, the effect of domestic laundry processes on the wear of fabrics has also led to discarding clothes faster than they are produced; which in turn has significant environmental impact arising from cradle to grave production of cheap and low quality materials. The life cycle performance and properties of the fabric are altered as a result of wear, machine laundry and tumble drying (Agarwal *et al.* 2011d). Therefore, the laundry life cycle performance must be evaluated, to maintain the durability and aesthetic value of the fabric during its lifetime.

Consequently this thesis, first, aims to examine the potential benefits of adopting polylactic acid (PLA) as an alternative to cotton and polyethylene terephthalate (PET) by exploring the life expectancy and durability of the fabrics. Secondly, to evaluate the environmental performance during the experimental “use” phase and when the durability is optimised to have a longer life expectancy.

1.3 Objectives

The above aims will be achieved by fulfilling the following research objectives:

- To determine the laundry regime that best expresses the fabrics’ end of use through changes in tensile properties of PLA, PET and Cotton
- To evaluate and compare the environmental performance of polylactic acid, cotton and polyethylene terephthalate material from cradle-to-usage, using tensile properties as indicators of fabric performance
- To assess the suitability of PLA as a substitute for Cotton or PET by lifecycle assessment.

This research provides an original approach to assessing the overall life cycle environmental impact of cotton, PET and PLA fibres used in fashion fabrics. In particular, it focuses on the most significant "use" phase where laundering plays a dominant role. A lifecycle assessment model or system was developed for predicting the quantity of input material fabrics need to improve the fabric lifetime factor to 75 laundry cycles, as well as to evaluate any environmental impact associated with this. The choice of 75 laundry cycles as calculated below is based on the number of laundry washing a uniform is subjected to in a typical school year.

1.4 Research Hypothesis

Based on the objectives of this research, the following hypothesis for the dependent variables (load at break, tensile modulus, percentage extension at break and tensile strength) are listed below. The null hypothesis (Ho) is that there is either no significant effect or interaction of the independent variables (laundry regime and laundry treatments) on the properties of the fabrics and the alternative hypothesis (Ha) is that there is an effect of the variables on the properties of the fabric.

Hypothesis 1

a. Ho_1: There is no significant effect of each laundry treatment on the properties (load at break, tensile modulus, percentage extension at break and tensile strength) of the fabrics during the laundry regime.
b. Ha_1: There is a significant effect of each laundry treatment on the properties (load at break, tensile modulus, percentage extension at break and tensile strength) of the fabrics during the laundry regime.

Hypothesis 2

a. Ho_2: There is no interaction between the laundry regime and the laundry treatments on the tensile properties of each fabric.
b. Ha_2: There is an interaction between the laundry regime and the laundry treatments on the tensile properties of each fabric.

Hypothesis 1 will determine if the mean tensile properties of the five replica specimens are different between the laundry regimes (unwashed, one, three, six, 10, 30 and 50). Hypothesis 2 will determine if the effect of the interaction between the laundry regime and the laundry treatments on the tensile properties of each fabric is significant. This is to ascertain the effect of the different laundry treatments in relation to the increasing washing cycles.

1.5 Evidence of Originality and Innovation of this research

This research has modelled and compared, through extensive laundry regime, the impact of laundry on the mechanical properties and environmental performance of PLA compared to PET and cotton fabric using the GaBi 4 life cycle assessment tool introducing a lifetime indicator as a link between the tensile properties and the number of laundry cycles each fabric can endure during their lifecycle. A life cycle assessment (LCA) was developed to examine the benefit of adopting PLA as an alternative to PET and/or cotton, and to predict and compare, through the laundry "use phase" the environmental impact of producing durable fabrics (Figure 1.5). In addition, applying the LCA model proves that PLA could serve as an alternative to PET and cotton even with extended life expectancy.

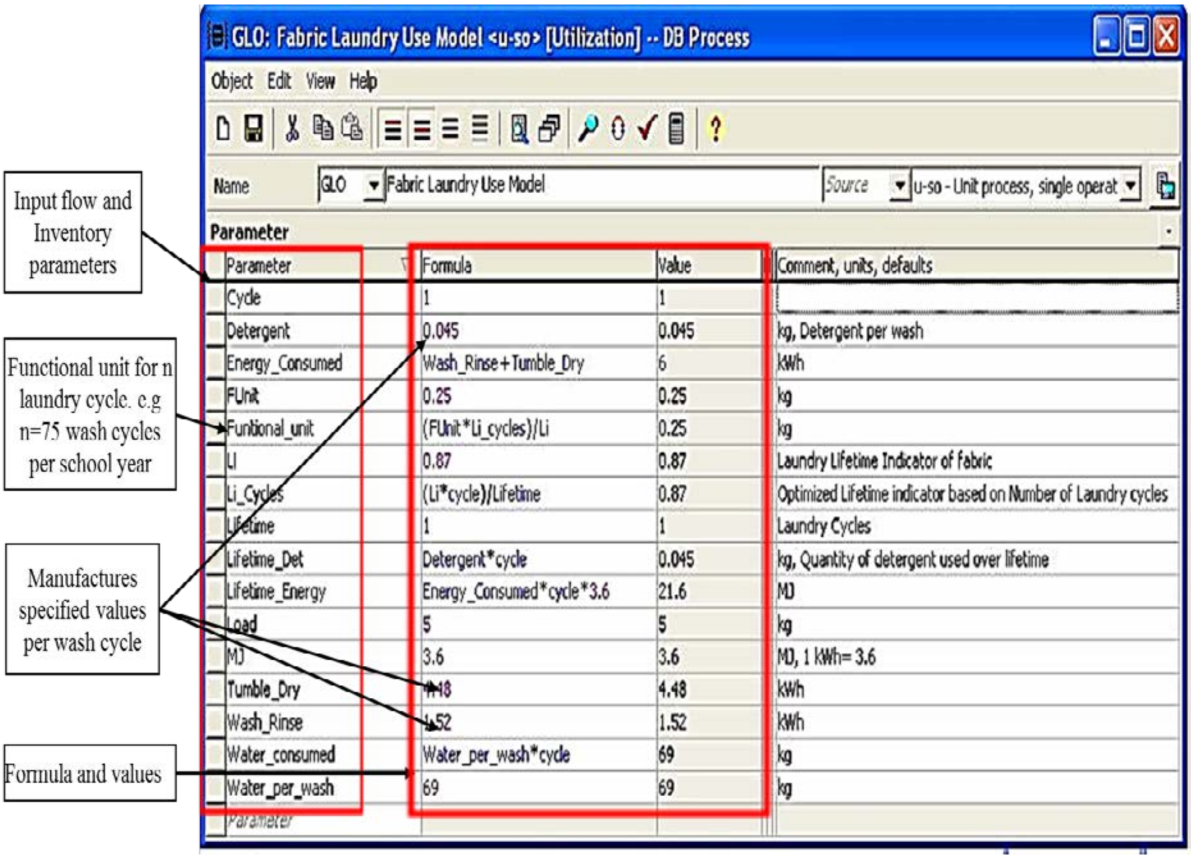

Figure 1.5: Use-phase process developed to model the effect of laundry lifetime and the environmental impact of fabrics using the tensile properties as indicators of performance. (Source: Author)

The results produced could help manufacturers to ascertain the material’s life expectancy from the production stage and to determine life cycle environmental impact of different quality fabrics. In addition, the results are useful for policy makers and consumers in decision-making when acquiring clothes or textile materials, also the results contribute to the limited body of knowledge on the existence of fabrics made from PLA in comparison to conventional materials.

2 LITERATURE REVIEW

2.1 Introduction

The key aim of this review is to identify where the textile industries stand in their ability to meet the 13.1kg per capita fibre consumption forecast (Schindler 2012); at the same time maintaining the quality and reducing the environmental damage associated with the textile industry. The focus is to review previous studies on the various environmental impacts generated because of the total reliance on PET and cotton fabrics used for this research. Factors such as low quality, growing population, fast fashion ánd wash performance that influences fabric life expectancy are reviewed, followed by the laundry practices and the durability. This is linked with environmental impact and the effects of laundering during the application phase of the fabrics studied. Material maintenance is most demanding during the use phase of the life cycle (Laitala *et al.* 2012). For example, mechanical damage occurs while laundering movements in the washing machine, abrasion, creasing and deposits on textile fibres (EMPA Research Institute 2002a). Water in any condition (hard or soft) has a predominant influence on the quality of laundered textiles (Lipus *et al.* 2013).

Fashion trends and changing lifestyles have also contributed in particular to the diversity of fibre types, fibre parameters, yarn construction and textile manufacturing. One decision-making factor on how long a consumer can, or will, keep a garment is its washing performance. Studies and research have already concluded that laundering is the primary offender in the damage experienced by fabrics during their application or use phase. For example, the weight and stiffening of cotton, the felting of shrink-resistant wool at standard machine agitation levels and the stretching of acrylic fabrics in tumble-drying were identified as some of the factors that make consumers become dissatisfied with a garment (Mackay *et al.* 1999).

2.2 Fabric life expectancy

Despite the influence of fast fashion and high impulse purchasing on discarding of textiles products before their end of life (Bianchi and Birtwistle 2010), the primary factor that determines the lifetime of textile clothing during the use phase is its laundry performance. According to Neelakantan and Mehta (1981), a cotton garment can withstand 30-50 washing cycles before showing significant damage despite the difference in laundry practice. Other literature has also demonstrated that a garment’s life cycle or life expectancy is considered to be between 30-40 laundry cycles (Agarwal *et al.* 2011c, Lau and Fan 2009), which is ten cycles less than the previous estimate. This is linked to the production of low-quality fabric that cannot withstand the mechanical, chemical and heat actions during laundry processes like washing, drying and ironing. The effect of laundry on fabrics’ life expectancy has taken precedence over wear and tear and the influence of fashion (Lau and Fan 2009).

According to Ren (2000), the quality and nature of a fibre or fabric can have an impact on the maintenance of the textile. In other words, the quality of the material determines how many times the material is washed during its useful lifetime. As a result, the first step to the sustainability of a product is to enhance it during its manufacturing process (Cepolina 2012). Consequently, environmental performance is a measure of consumers’ and stakeholders’ use as criteria before dealing with suppliers (Boiral and Sala 1998, Hamner 2006).

2.2.1 Impact of fast fashion on fabric life expectancy

Fashion, as defined by Moon *et al.*(2013), is a unique and tangible consumer product with features such as timelessness, style, trendiness and many knocks offs. It is characterised by the evolution of trendy design into articles easily acquired by the growing population (Sull and Turconi 2008). It is the consumers most purchased non-food product, no more a necessity, but a must-buy for every season (Solomon and Rabolt 2011). In the last 25 years retail consolidation, globalisation and e-commerce have influenced the radical evolution of the textile/fashion industries (Mehrjoo and Pasek 2014).

As consumers become more fashion conscious, more unnecessary and short lifecycle products are manufactured (Bailey 1993, Mehrjoo and Pasek 2014). As a consequence, a greater environmental burden is exerted on the textile industries from increasing greenhouse gas (GHG) and CO_2 emission via transportation (Saicheua *et al.* 2012), use of chemicals and non-renewable natural resources (de Brito *et al.* 2008). The consequence of a fast fashion culture is the high and constant increase in energy consumption (Ngai *et al.* 2012). As a result, environmental performance is now part of consumers and stakeholders' criteria before dealing with suppliers of textiles materials (Boiral and Sala 1998, Hamner 2006).

2.2.2 Impact of growing population on fabric life expectancy

It is imperative that the world's population, expected to reach 9.1 billion by the year 2050, will need some form of clothing to cover their nakedness (UNDESA 2013). Therefore, to satisfy their textile needs will ultimately require intensifying the production of unnecessary and short lifecycle products. There is a gap in terms of literature on the impact of the world's growing population on the life expectancy of textile materials. However, since the expected increase in population will put a strain on demand for textile fabrics, the production of synthetic fibres from natural resources will not only be integral in the textile market and economic development but also play a significant role in meeting increasing demand. According to Pakula and Stamminger (2010) (2010), a third of the world's population, consisting of 780 million households in 38 countries consumes approximately 100 TWh of electricity and 20 billion m^3 of sanitary water per year.

2.3 Laundry Practice

As mentioned in Section 2.2, the primary factor, that determines the lifetime of textile clothing during the use phase, is its laundry practice. The vast difference in the types of household determines the frequency and the type of laundry practices (Arild *et al.* 2003). In addition, washing temperatures, colour, fibre types and level of use or soiling are factors that influence laundry practices (Laitala *et al.* 2012). From the survey on patterns of water use in southern England, Pullinger *et al* (2013) found that 95% use the washing machine as the main way of laundry, 45% use a tumble dryer. They also found that, of the 95%, three-quarters run their washing machines 2-3 times a week with a full load (≥5 kg), without changing the setting. Table 2.1 shows six types of laundry practices also identified by Pullinger *et al.* (2013).

Adapted from (Pullinger *et al.* 2013) .

In the study carried out by Laitala *et al* (2012)., detergent dosage per washing was done by eye measure and based on the amount of laundry or level of soiling of the fabrics.

2.4 Fabric tensile properties

The property of PLA fibres depends greatly on the collection rate, the higher the collection rate, the higher the modulus and the strength of the fibre, the lower the strain at break. These fibres stretched to a useful tensile strength of 0.87 GPa (Fambri *et al.* 1997). NatureWorks PLA polymer has a tensile strength of 44.46 MPa and Young's modulus of 3.11 GPa, the density of 1.24 g/cm^3 and melting temperature 160-170^{o}C (Bax and Müssig 2008). Table 2.2 shows the properties of PLA fabric compared to PET and cotton.

Source (Avinc and Khoddami 2009)

2.4.1 Influence of tensile properties on the life expectancy of fabrics

Fabric tensile properties are important deciding factors in the performance and longevity of fabrics, garments or textiles in general. Several authors have shown that material mechanical properties are an integral part of its life expectancy. During the everyday use of fabrics, they undergo changes, and the way they respond to these changes, depends on the mechanical properties that can only be described by the changes in their fibre, molecular and structural properties(Zupin and Dimitrovski 2010).

During use, fabrics undergo repeated cyclic tension that tends to weaken the properties. For instance, Otaghsara *et al* (2009) studied the tensile and fatigue behaviour of different knitted polyesters and concluded that the structural parameter of the fabrics has an influence on the tensile and fracture behaviour of the fabrics. However, during use that was simulated by repeated laundry cycles, the fabric experienced yarn straightening and loop deformation that only recovered with time. The effect of this is stress relaxation of the constituent yarns in the fabric and secondary creep, i.e., non-recoverable fabric extension (Otaghsara *et al.* 2009)

2.4.2 Effect of laundry treatments on fabric tensile properties

Everyday life laundering is a recurring phenomenon in the life cycle of fabrics. The process involves scrubbing, a copious amount of water and chemical detergents to remove dirt, elevated temperature, wash cycle duration coupled with the effect of mechanical agitation and method of drying (Avinc and Khoddami 2010, Gore *et al.* 2006, Higgins *et al.* 2003, Slater 1991). As a result, the fabrics experience changes to fibre content, yarns, surface and mechanical properties.

Several studies have presented detrimental effects of laundering on properties of fabrics. For example, Lau *et al* (2002) studied the effects of repeated laundering on the performance of garments with wrinkle-free treatment. The study looked at the resistance, softness, air permeability and tensile properties of polo shirt fabric and found a significant decrease (Figure 2.1) in the tensile properties after 12 washing cycles with the resilience value decreases by 10-20% after 16 washing cycles.

Figure 2.1: Decrease in the tensile properties (tensile extension) of polo shirt fabric (Lau *et al.* 2002)

Duru and Candan (2013) studied the effect of repeated laundering on wicking and drying properties of fabrics of seamless garments. The study looked at the moisture management and dried properties of cotton, viscose and bamboo after five repeated laundry processes. The results show that repeated laundering processes affect the fibre and fabric properties, which leads to changing the performances of the fabrics.

In comparison, this study concluded that the liquid transfer properties of cotton fabric makes it suitable for normal use but unsuitable under strenuous application. Furthermore, the properties of viscose fabrics decline during laundering making it less suitable for use in next-to-the-skin applications. However, the laundering process improved the liquid transfer properties of the bamboo fabrics, making it the best alternative to viscose or cotton.

Li and Shi (2011) studied the effect of washing time on the fuzz and pilling performance of wool/polyester fabric (Li and Shi 2011). The study found that the anti-pilling property deteriorated with increasing washing time. In the repeated domestic laundry of cotton fabric to determine the effect on colour properties, Mangut *et al.* found that the colour fastness decreased gradually after 20 laundry cycles (Mangut *et al.* 2008). Studies have also been conducted on sensory properties (Agarwal *et al.* 2011a), dimensional stability and wicking (Anand *et al.* 2002, Higgins *et al.* 2003), fabric drape, bending and shearing (Orzada *et al.* 2009), tensile properties (Senthilkumar and Anbumani 2012, Mukhopadhyay *et al.* 2004, Munshi *et al.* 1993) and the durability (Handy *et al.* 1968). From these studies most damage or changes to fabrics or textiles occur after the first five to 10 wash cycles (Anand *et al.* 2002, Gore *et al.* 2006, Higgins *et al.* 2003).

Orzada *et al.* (2009) conducted a study on the effect of laundering on the drape, bending and shear properties of cotton fabric under three cycles (unlaundered, one and five home launderings). The study found that five laundering cycles had no significant effect on these properties of the cotton fabric. However the drape value increased overall (Figure 2.2) while the shear and bending modulus decreased (Figure 2.3) with increasing wash cycles.

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Figure 2.2: Increasing drape of cotton fabric with increased laundry cycles. Source: Orzada *et al.* (2009)

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Figure 2.3: Cotton bending properties decreasing after five laundering cycles Source: Orzada *et al.* (2009)

The lack of a variety of fabrics and a limited number of wash cycles posed a limitation to this study. Hence the recommendation of extra laundry cycles with the objective of assisting apparel manufacturers in developing laundry recommendations based on the fabric's performance and selection as well as maintaining their characteristics, mechanical properties, and dimensional stability with use (Orzada *et al.* 2009).

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Mackay *et al.* (1999) studied the changes in the sensory and mechanical properties of acrylic, cotton and wool with repeated laundering. Under a variety of washing and drying conditions (see Table 2-3), the study identified various factors that contributed to consumers dissatisfaction with the laundry performance of fabrics.

Table 2-3: Experimental designed used by Mackay *et al.* (1999)

These factors include the weighting and stiffening of cotton by the calcium phosphate deposit, the felting of wool at a regular washing machine agitation programme and stretching of acrylic fabrics. The study showed that, after 50 wash/dry low agitation cycles, the fabrics washed in water and line dried shrink between -5.0 and -11%, after load 1 while the fabrics washed in water and tumbled dried shrink between 0 and 1.9% after load 2. On the other hand, the fabrics washed in detergent and tumble dried shrank between 0.6 to 4.8%. After 25 wash/dry normal agitation cycles the fabrics washed in water and tumbled dried shrank between 1 and 39% after load 4, while the fabrics washed in detergent and tumble dried shrank between 2 to 48%. In general this study has been able to identify and attribute specific changes in fabric properties to laundry processes such as agitation level, detergent application and drying method.

2.5 Factors that affect fabric performance during laundering

Fabric performance is the key to its durability during use. As mentioned in section 2.2 degradation and deterioration are provoked by laundering. In addition repeated laundering is used to assess the performance of fabrics during their lifetime, s shown by everal studies such as Kan and Yuen (2009). Table 2.4 show the factors that influence the washing results of fabrics. There are many factors that affect the performance.

Table 2-4: Factors that influence the result of fabric washings

Adapted from (EMPA Research Institute 2002b)

In addition to these factors above, tumble drying also influences the performance of fabrics during their lifetime. For instance the study carried out by Brown (2000) on the effect of laundering on the dimensional stability and distortion of knitted cotton fabric concluded that a combination of low agitation and drying temperature caused the fabric to show excessive dimensional change.

2.6 Textiles and the Environment

The three top environmental issues in the textile industry are water use and pollution, energy and chemical use. Environmental impacts of textile products are categorised by fibre types; man-made synthetic or natural fibres (Figure 2.4). Synthetic fibres are produced from non-renewable, petrochemical based resources require a vast amount of chemicals and are non-biodegradable (Vroman and Tighzert 2009, Hopewell *et al.* 2009, Lligadas *et al.* 2013, Ghanbarzadeh and Almasi 2013). The manufacturing process starts with the production of monomers, followed by a polymerisation process from which the fibres are extracted. The fibres are then spun, drawn and pressed into bales. Natural fibres, on the other hand, are derived from agricultural products or animal sources. The fibres are extracted and processed in different textile applications.

Figure 2.4: Classification of natural and man-made synthetic fibres

Adapted from: (Rowell 2008)

The last century saw a dramatic change in the production of textile products with the introduction of man-made cellulose fibres. These are synthetic polymers made from natural resources such as wood pulp and cotton. Examples are viscose, lyocell, Tencel and Modal. However, the depletion of petrochemical-based materials and an increasing environmental awareness have paved the way for the invention and development of natural polymer-based bio-renewable materials (Thakur and Thakur 2014, Banerjee *et al.* 2013, Bogoeva-Gaceva *et al.* 2007).

2.7 Textile Durability and the Environment

Consumers are now aware of industrial pollution, waste and global warming related to the textile industry (Sule 2012, Woolridge *et al.* 2006). For example 4-5% of the municipal solid waste in the UK consists of clothes and textiles (Woolridge *et al.* 2006). This is expected to rise as the quality and durability of textiles has declined from 60% in 2006 to 43% in 2009 while household waste has increased from 2.83% to 4.10% (Morley *et al.* 2009). As a result, this has led to consumer dissatisfaction with the increasing environmental impact of the products they buy (Chen and Burns 2006). Hence studies such as Schor (2005), Das (2008) and Tyagi (2003) have reviewed the prices and qualities, unsustainable consumption, global economy, textile consumer pattern and environmental impact of durable fabrics compared to the cheap quality material (Das 2008, Schor 2005, Tyagi 2003). These studies have concluded that the overall lifecycle of a textile is getting shorter due to poor quality and quick replacement (De Saxce *et al.* 2012). The consequence of this is an increase in waste and environmental pollution through toxic chemical emission into the air or groundwater (Fletcher 2008, Niinimäki and Hassi 2011).

In the project on the influence of textile durability on environmental impacts, it was found that when the lifetime of a t-shirt increases, the effect on the environment decreases (Leffland *et al.*

1997). This view was also supported by the study on the present and future sustainability of clothing and textiles in the United Kingdom (Allwood *et al.* 2006), which concluded that the longer clothes are kept and maintained, the lower the environmental impact.

2.8 Textile Durability and Lifetime

PLA can replace existing polymers where renewable resources are a benefit or where additional performance is required (Drumright *et al.* 2000). During a study to determine the durability of 100% PLA fabric, it was washed 100 times, the bursting strength dropped slightly after the 75th wash with no significant loss in molecular weight after the 100th wash (Nature Works 2005).

Though various studies have presented the benefit of a PLA, and its blends, there are still some issues with the proportion of mixtures to get the right mechanical properties (Bax and Müssig 2008, Bourmaud and Pimbert 2008, Hu and Lim 2007). Low volume of reinforced fibre resulted in a reduced effect of the matrix, while a higher amount may induce a defective bonding between the fibres and the matrix (Xiao-Yun *et al.* 2010). Hence, the type of composite materials used plays a significant role in the fibre/matrix adhesion and thereby affects the mechanical performance of the bio-composites (Jayaramudu *et al.* 2013). For instance, when 30% of ramie fibres were mixed with PLA fibres, the flexural strength of the composites decreased far less than pure PLA (Yu *et al.* 2009).

This outcome was also confirmed when PLA/flax matrix was tested showing that 35% flax fibre content exhibited the best mechanical strength (Xiao-Yun *et al.* 2010). Bajpai *et al.* (2012) concluded that fibre brittleness reduces due to composite incorporation, which in turn increases the percentage elongation at break of PLA/nettle or sisal matrix. For reasons still unknown, a reduction in impact strength was recorded for PLA/nettle matrix when compared to 100%. It was suggested that the stress concentration region formed by the fibre bundles could have caused a reduction in impact straight with less energy (Bajpai *et al.* 2012). Evidence from a recent study showed that the use of conventional extrusion followed by injection moulding for the fabrication of pulp fibre and PLA matrix yielded weak and sometimes negative tensile strength, reduction in fibre lengths and damage to the fibres (Du *et al.* 2014). However combining an extra wet-laid sheet-forming process with the conventional process, the matrix showed superior modulus and tensile strength reinforcement. This confirms the premise that manufacturing of durable textile products requires the introduction of additional processes and/or the use of different materials and process (De Saxce *et al.* 2012).

2.9 Lifecycle Assessments

The only method that evaluates the environmental impact of a product over its lifecycle is Life Cycle Assessment (LCA) (Tobler-Rohr 2000). This takes into account and evaluates potential types of impacts associated with raw material extraction, manufacturing, transportation and distribution, use and disposal of the product. Several studies have used LCA to evaluate impacts related to the textile industries and its process. For example, the LCA of fabric and textiles from fibres to end of life (Kalliala and Nousiainen 1999a), the impact of producing hemp and flax fibres (Van Der Werf, and Hayo 2004, Van Der Werf. *et al.* 2008), cotton and PET fabrics (Kalliala and Nousiainen 1999b), and the analysis of cotton towel during the use phase (Blackburn and Payne 2004). LCA in the textile industry, especially textiles made from the natural polymer cellulose such as cotton and corn involves system modelling using site-specific data and different farmers' strategy. It is also possible to measuring and comparing the carbon footprint and different environmental indicators of different fibres or textile products (Muthu 2014a).

2.9.1 Production and Manufacturing

Figure 2.4 shows a flow diagram of the various processes involved in the manufacturing of textiles from raw materials to the finished product. The method of producing textiles is complicated, as many of the processes do not occur at a single facility due to the wide variety of substrate, processes, machinery, and diversities of fabric (Hasanbeigi and Price 2012). The various processes shown in Figure 2.5 are important since the quality and yield of fibres uses in textile production is greatly influenced by the growing conditions, harvesting and the methods employed in processing (Pervaiz and Sain 2003). Also, to have a holistic picture of the environmental impacts of each fabric studied, it is important to take an inventory associated with each process.

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Figure 2.5: The textile chain flow diagram.
Adapted from (Hasanbeigi and Price 2012)

Activities during the whole life cycle, from the production, manufacturing distribution and use of textile products add to the already existing pollutants to the environment. There is a link between the ongoing environmental damage and the textile industry (Patterson 2012). The production of textiles and fashion-related products requires 10-175 MJ of energy, consumes between 43-24,000 litres of water and contributes 2-9 kg CO_2 and global warming to the environment (Hasanbeigi and Price 2012, Meier *et al.* 2015, Volmajer Valh *et al.* 2011). For example, a t-shirt weighing 0.25kg has been reported to consume 2.56 MJ of energy, producing

$0.16kg\ CO_2$, 0.46g particulate matter and 0.96-0.99g of NO_x and SO_2 respectively (Muthu 2014b).Table 2.5 shows the water requirements, global warming potential and the energy use for both the processing and cooling process for the production of 1kg of fibres.

Adapted from (Muthu *et al.* 2012)

Water requirement for natural fibre differs from synthetic fibres based on the process of production (Muthu *et al.* 2012).

2.9.2 Cotton

Cotton is the most important natural and widely used fibre for the manufacturing of textile garments (Acquaah 2007, Muthu 2014b). Due to its high water and moisture absorbency, wear comfort and ease of dyeing, it dominates the apparel industry with a total fibre share of 50% (Karmakar 1999) cited in Hashem *et al.* (2010). Its excellent performance properties such as hydrophobicity and high static electricity discharge make cotton very comfortable to wear compared to synthetic polyester or acrylic fabrics (Abdel-Halim *et al.* 2014). The primary producers of 70-80% of cotton are the USA, Turkey, India, China, Pakistan and Uzbekistan (ICAC 2014). Figure 2.6 shows the quantity of cotton produced between 2012/13, 2013/14 and 2014/15 by the top countries in million tonne.

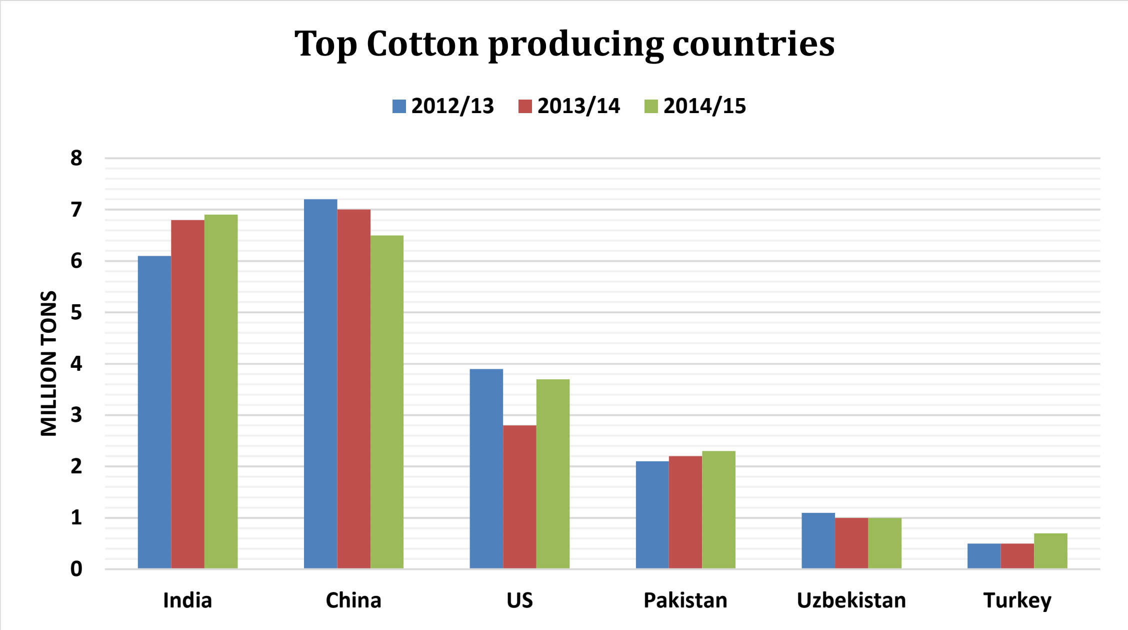

Figure 2.6: Production of cotton by countries in million tonnes in 2012/13, 2013/14 and 2014/15

The excellent performance of cotton is due to soft comfortable hand, good absorbency, colour retention, machine washability, strength and drape properties. As a natural cellulosic fibre, cotton is constituted of the following components listed in Table 2.6. Over 90% of the fibre is made up of cellulose, which is a polymer consisting of anhydroglucose units connected with 1,4 oxygen bridges in the beta position. The hydroxyl groups on the cellulose units enable hydrogen bonding between two adjacent polymer chains. The degree of polymerization of cotton is 9,000-15,000. Cellulose shows approximately 66% crystallinity.

Table 2-6: Composition of a typical cotton fibre

Constituent	**Composition (% dry weight)**	
Typical		Range
Cellulose	94	88-96
Protein	1.3	1.1-1.9
Pectic substances	1.2	0.7-1.2
Ash	1.2	0.7-1.8
Wax	0.6	0.4-1.0
Total sugars	0.3	
Pigment	Trace	
Others	1.4	

Adapted from Proto *et al* (2000)

Several studies have outlined the various processes of producing cotton from growing, spinning, weaving and laundering. The process of producing cotton fibres includes sowing of cottonseed, cultivation and harvesting. Cotton, either grown organically or not, always leads to a negative consequence of water salinity and water-resource depletion. It is the most expensive fibre to produce, requiring high water usage; 22,200 litres during farming, 3,900 during manufacturing of fibre products and 49 litres per wash for textiles and apparel. It also attracts pests therefore chemicals are used during cultivation and storage. According to Zwart and Bastiaanssen (2004), cotton uses about the same amount of water as other major crops (Zwart and Bastiaanssen 2004). In fact, the global water footprint of cotton, measured to be about 2.6%, is lower that soybeans 4%, maize 9%, wheat 12% and rice 21% (Hoekstra and Chapagain 2007).

Production, use phase and waste management stages of the life cycle of cotton has been compared with polysaccharide-based fabrics and PET fibre (Kalliala and Nousiainen 1999b). In both cases, cotton showed reduced environmental profile in terms of non-renewable energy use and greenhouse gas emission while polysaccharide-based fibre has lower non-renewable energy consumption than petrochemical-based fibre. Cultivation of traditional cotton has ecotoxic effects because it requires the use of pesticides and fertilisers, and 7-29 x $10^3 kg_{cotton}$ of irrigated water compared to 17l kg of water consumed in the production of polyethylene terephthalate fibre.

2.9.3 Polyethylene terephthalate

Like cotton, polyethylene terephthalate (PET) is a thermoplastic polymer synthesised by the esterification of terephthalic acid (TPA) and ethylene glycol (EG) or by the transesterification of dimethyl terephthalate (DMT) and EG. Fibres fall under the category of man-made or synthetic fibres and can also be classified as petrochemical-based and cellulose-based. PET is a type of polyester, produced by the polycondensation of the terephthalate acid (TPA) with ethylene glycol. It is the second most popular fibre after cotton according to the measured production tonnage (Hashem *et al.* 2010). Production of PET fibres has a high environmental impact in terms of use of energy, CO_2 emission and health hazards during the entire lifecycle from production to final disposal (Slater 2003). Smith and Barker (1995) carried out one of the earliest studies on the lifecycle assessment of polyester fabric. The study used a functional unit of 1 million wearing cycles and showed that 82% of the total energy requirement is associated with consumer use, 18% was attributed to manufacturing while disposal was less than 1% (Figure 2.7). No water requirement was included in this study; however, a total of 254kg of chemical oxygen demand (COD) was emitted to water via process and fuel-related pollutants .(Smith and Barker 1995).

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Figure 2.7: Total energy requirements per million wearings
Adapted from (Smith and Barker 1995)

In the LCA study by Kaillala and Nousiamen (1999) the production of 1kg of PET was reported to consume about 97.4MJ of energy, 17.2kg of water; resulting in the emission of 2.31kg of

CO_2, 19.4g of NO_2, 18.2g CO, 39.5g CH and 3.2g COD (Muthu 2014b). Compared to PET, cotton is not as energy intensive; it, in fact, has the lowest cumulative energy demand among all the fibres studied by (Shen and Patel 2010).

2.9.4 Polylactic acid

Polylactic acid is a bio-based thermoplastic polymer, which has been widely used in various applications such as tissue engineering, slow release drug delivery, packaging composites (Cont *et al.* 2013, Vieira *et al.* 2011). However, only recently has the potential of PLA shown a promising application in the textile industry (Gupta *et al.* 2007, Gross and Kalra 2002, Dartee *et al.* 2001, Lunt and Shafer 2000, Zupin and Dimitrovski 2010). The study and application of the PLA fabric have been investigated extensively in recent years. Polylactic acid fabric is made from melt–processable aliphatic polyethylene terephthalate derived from entirely renewable and natural sources; corn starch (Landis *et al.* 2007, Ohkita and Lee 2006, Vink *et al.* 2003, Wang *et al.* 2003) or sugar beet (Calabia and Tokiwa 2007, Finkenstadt *et al.* 2008, Finkenstadt *et al.* 2007, Liu *et al.* 2005). The synthesis of polylactic acid fibres requires only 0.02% of the total corn produced worldwide, so this does not pose a threat to food production (Sawada and Ueda 2007).

The goal and objective of the LCA of PLA production carried out by Cargill Dow is to reduce the fossil fuel energy use from 54 MJ/Kg to 7 MJ/Kg and the GHG from +1.8 to -1.7 Kg CO_2 Eq/kg (Vink *et al.* 2003). Detailed studies regarding specific product application have not been published due to the sensitive natureLifecycle inventory data. Vink *et al*. (2003) measured the environmental performance of PLA using three life cycle impact categories: fossil energy requirement, greenhouse gases and water consumption. The gross fossil energy demand accumulated throughout the life cycle, from corn cultivation to the production of PLA pellets is 54 MJ/kg.

Through LCA, Cargill Dow was able to identify operational strategies that will efficiently improve and eliminate fossil fuel use as mention above to 7 MJ/Kg. Due to the relationship between fossil fuel energy and other impacts associated with air, water, and waste emission, the by-product from Lactide (lignin) and renewable wind power used as an alternative to fossil fuel will give gives an additional reduction 1.35 CO_2-eq./kg PLA (Vink *et al.* 2003).

2.9.5 Consumer Use Phase

Over a textile product's life cycle, the consumer use is one of the most importance phases as this contributes the major environmental impacts. Several studies have dealt with the environmental impact arising from the consumer use phase for laundry of various textile products. For example in the environmental assessment of textiles, a 100% cotton t-shirt was subjected to a typical use phase consisting of domestic washing and drying, the largest contribution to environmental impact came from the electricity use, and emissions associated with energy consumed by both processes (Laursen *et al.* 2007). Figure 2.8 shows a range of consumer use scenarios that explains the relationship between the use pattern and the product life per energy consumption.

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Figure 2.8: Life cycle energy requirement for a range of use scenarios of a polyester blouse per wearing

Adapted from (Franklin Associates 1993)

The life cycle assessment (LCA) of a woman's polyester blouse shows that the majority of impacts occur during the laundry use phase and not in its production or disposal (Franklin Associates 1993). The study concluded that 82% of the energy, 83% CO_2 emissions to air, 66% waste generated and 96% emissions to water (Biological Oxygen Demand) was associated with the use phase (washing and drying) only. However, the environmental impact generated during the use phase of washing and drying of clothes can be reduced by 50% if they are washed half as often (Allwood *et al.* 2006).

The results from individual LCA studies have only limited significance for the life cycle assembly of textiles, since there are too many diverging parameters, particularly in quality aspects. Even the same fabric produced with different process technology, or on different equipment or with various formulas will result in different impacts. Kalliala and Nousiainen (1999a) used data from LCA inventory of several sources with the aim of increasing awareness of the environmental impact associated with the production of fabrics for hotel textiles services. Two types of fibres considered for this purpose are cotton and polyester-cotton. The study concluded that the manufacture of cotton fibre had a less environmental impact compared to polyester-cotton fibre. In the use phase of these fibres, it was found that the potential lifetime of the polyester-cotton fibre was twice as long as the cotton fibre.

The goal and scope of the lifecycle assessment of cotton towel was intended to determine the impact of domestic laundering on the cotton towel, and to find out whether techniques used to reduce washing frequency can provide an overall greener lifecycle for the cotton product (Blackburn and Payne 2004). The study was carried out using data collated from previous studies and databases. The lifecycle looked at the production, the product utilisation and consumer-care phase and the disposal stage. Impact categories considered at different stages were extracted energy and water consumption at both cultivation and fibre-processing stage, and laundering and drying stage. Since there was no evidence of cotton towel recycling, it was assumed that they were disposed of in landfills.

Figure 2.9: Extracted energy consumption (kWh) of towels over lifetime
Source (Blackburn and Payne 2004)

Figure 2.9 shows that the most critical stage of the life cycle over its lifetime is the consumer phase. Therefore, for cotton towels, any change leading to a reduction in energy within the consumer stage will result in a significant decrease in the energy consumed in the entire life cycle.

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3 METHODOLOGY AND EXPERIMENTAL DESIGN

3.1 Introduction

This chapter embarks on describing the fabric materials used in this research and then moves on to explain the experimental, statistical and the LCA modelling approach used to achieve the aims and objectives set out in Chapter 1 of this study. Figure 3.1 shows the schematics of the experimental design for this study. It focuses on the lifecycle of a 250g t-shirt with particular concentration on the use phase. From lifecycle inventories of the production and consumption of a T-shirt, the use phase by consumers has been identified as the largest contributor to environmental impact (Steinberger *et al.* 2009).

Figure 3.1: Schematics of experimental design and methods

A detailed description of the experimental aspect of this study involving the use of a laundry regime to illustrate the impact of the use phase in the overall life cycle of PLA, PET and cotton is provided in Section 3.2.2. The methods and parameters described were performed to simulate a consumer's real-life situation as close as possible. These follow an outline of the method of material testing (Section 3.3) used to determine alterations in tensile properties of the fabrics after 50 wash cycles.

Before the main experiment, a pilot laundry and tensile experiment (Section 3.2.1) was performed on the three fabric types, PLA, PET and cotton, to test the feasibility, gather information and to reveal any deficiencies in the design of the main study. The advantage of conducting a pilot study was to explore any advance warning of the failure of the main research, to verify an appropriate research protocol and to test if the proposed method, equipment and materials are adequate or too complicated.

3.2 Materials

For this study, 100% cotton, polylactic acid and polyethylene terephthalate fabrics were used. These fabrics were chosen to represent the different categories of available fabrics and due to their different physical, chemical properties and different market relevance. The PLA was sourced from Jinsor-Tech Industrial Corp in Taiwan while the cotton and PET were sourced locally in the UK from Whaleys (Bradford) Ltd. The characteristics of the chosen fabric samples are shown in Table 3.1.

Table 3-1: Characterisation of fabric samples, plain weave, (length x width: 200 x25mm)

Fabric	*Warp Yarn*	*Weft Yarn*	*Density(g/m^3)*	*Thickness (mm)*
PLA	92	62	110	0.23
PET	92	62	150	0.23
Cotton	40	40	130	0.35

A front loader Hotpoint washing machine (Figure 3.2) with model WMD960 Ultima with eco function and super silent was used for the laundering. A front loader Hotpoint Dryer (TCL770 Aquarius) was used according to procedure C of the ISO standard for tumble drying at an average of 40^oC due to the low T_g of PLA (58-65^oC).

Figure 3.2: Hot Point washing machine model WMD960 Ultima with eco function and super silent

3.2.1 Pilot Laundry Regime and conditions

The pilot laundry test was performed using a laundry regime of 1, 10, and 50 wash cycles in a laundry programme set at 1600rpm, 40^oC cotton wash for 2:37 hours. After each laundry cycle, the fabrics were dried in the tumble dryer at an average of 60^oC according to procedure C of the ISO standard for tumble drying due to the low T_g of PLA (58-65^oC).

During the initial pilot experiment, all three fabric specimen samples cut into 20 x 2.5cm strips frayed considerably after the laundry cycles. Consequently, the results of the mechanical tests were inconsistent due to the reduced width of the samples. Large sizes of the samples were washed before cutting into test specimens to overcome this issue. During the pilot test, various loads ranging from 1kg to 5kg were washed and the decision to settle for 5kg laundry load was made (Table 2.1). At this load, a better representation of consumer laundry practice was presented, with the uniform disposition of water, detergent and mobility for friction between fabric and the wall of the machine to achieve a higher mechanical influence on the fabric materials. All materials were allowed to relax completely by keeping them at standard temperature and pressure, i.e.20 ± 2^{o}C; 65 ± 2%, RH for 24 hrs before laundering.

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Figure 3.3: Initial washing machine programme set at 1600rpm, 40^{o}C cotton wash for 2:37 hours for the pilot experiment

During the pilot test of the research, the laundry condition listed below was used. Figure 3.3 shows the duration (2: 37mins), spin speed 1600rpm to ensure that the fabrics experience enough agitation and contact with detergent.

a) One full load (≥5kg), same settings with a throughout the regime
b) No pre-wash
c) 40^{o}C cotton cycles due to the low glass transition temperature (T_g) of PLA (55-65^{o}C),
d) 45ml standard commercial non-bio Persil liquid detergent (manufactured by Procter & Gamble Ltd)
e) Tumble dried at 60^{o}C according to procedure C of the ISO standard.

3.2.2 Modified laundry regime

It was observed that the fabrics, (especially PLA) creased and crimped considerably when washed using the settings in Figure 3.3, which required ironing before they could be cut or were suitable for tensile testing. The difficulty in this is that PLA fabric melts at a temperature above its glass transition T_g point of 58-65^oC (Karst *et al.* 2008). Therefore, a modification was made to the washing and tumble dryer settings to avoid creasing. Figure 3.4 shows the modified configuration, using synthetics wash programme at 40^oC, 800rpm and a reduced time of 1:10 hrs since the fabric samples were not soiled before laundry.

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Figure 3.4: Washing machine programme set at 800rpm, 40^oC synthetic wash for 1.10 hours as there was no soil, and all fabric washed in the same laundry load

Since this study did not involve any wear and tear of the fabric samples, the laundry regime was limited to 50 laundry cycles which represents 10 cycles above its laundry life expectancy. The choice of 50 laundry cycles was based on previous articles such as (Neelakantan and Mehta 1981) who established that cotton garments could withstand 30-50 wash cycles. In addition, the studies performed (Agarwal *et al.* 2011b, Agarwal *et al.* 2011c, Agarwal *et al.* 2011d) adopted the life cycle of garments to be 40 wash cycles.

As identified in Chapter 2, laundry process, and its performance has improved over the years in particular by the reduction of washing temperatures and water consumption, the addition of fabric softeners, and different drying conditions. Therefore, in addition to the laundry conditions listed in Section 3.1.2, the influence of fabric softeners and drying conditions was also performed to explore the impact of different parameters such as;

a) Addition of 25ml Lenor fabric softeners per wash

b) Two drying conditions: tumble drying and air drying at room temperature.

All fabrics were subjected to a laundry regime under the same conditions and according to British Standard EN ISO 6330: 2001 (Domestic Washing and Drying Procedure for Textiles Testing). Table 3.2 describes the laundry regime and different conditions.

Table 3-2: Different laundry treatment and regime used in the research and analysis

Code	Laundry Condition	Drying condition	Laundry Cycles
DT	Detergent	Tumble (60^{o}C)	1,3, 6, 10, 30, 50
DA	Detergent	Air (room temperature)	
DST	Detergent and Fabric Softener	Tumble (60^{o}C)	
DSA	Detergent and fabric softener	Air (room temperature)	

Laundry conditions listed in Table 3.2 were chosen to ensure that all fabrics had the same treatment and to simulate the most common laundry practice performed by 36% of the UK population in which all washings are done with a full load (≥5kg), and the same washing machine settings (Pullinger *et al.* 2013) Table 2-1. Figure 3.5 shows fabric samples air dried indoors at room temperature. The temperature in the room is usually kept at about 20^{o}C to prevent damp and mildew on fabrics stored in the room.

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Figure 3.5: Air dried fabric at room temperature

3.2.3 Sample preparation

After each chosen cycle, five replica specimens measuring 2.5cm by 20cm strips were cut from the centre of the fabrics using a laser cutter as shown in Figure 3.6. Since the fabric samples used were plain weave, anisotropy was not considered. Therefore, the samples were cut along the warp directions of the fabric This was in accordance with ISO13934-1 and ASTM D5035-11 test standard.

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Figure 3.6: Strips of fabric specimens cut in rectangular 2.5cm by 20cm after each (1, 3, 6, 10, 30, and 50) wash cycle for tensile testing

3.3 Characterising the behaviour and tensile properties after laundry

A table mounted Universal Instron Model 5564 Tensile tester for fabrics with a load cell of 1kN was used for tensile testing during the pilot experiment. The test was performed according to the ASTM D5035-11 standard test for breaking load and elongation of textile fabrics and ISO 13934-1 mechanical test standard for textile tensile properties of fabrics: maximum force and elongation at maximum force using the strip method (Avinc *et al.* 2010). The crosshead speed for the pilot test was 10mm/min testing, with a gauge length of 125 ± 1 mm, using a pneumatic action grip to allow for equal pressure at both ends of the fabrics. However ,due to age and the discontinued support, this model was replaced by Instron tester model 3369 (Figure 3.8) when it broke. This model was fitted with a 50kN load cell, and the test parameters were modified to a crosshead speed of 100mm/min according to (Mitchell *et al.* 2005). The choice of sample size, gauge length and modified test speed are all subject to the aims and originality of this research and intended to minimise the duration of the tensile test.

Figure 3.7: Instron tensile tester model 3369, used for the fabric testing after each laundry cycle

The test was carried out under standard laboratory conditions (20 ± 2^{o}C; 65 ± 2%, RH) according to BS standard EN ISO 2062: 1995 as used by Avinc *et al.* (2006). The samples were secured to the Instron tensile tester with manual grips and stretched from a gauge length of 125 ± 1 mm between the grips at a constant rate of extension (CRE) and cross speed of 100 mm/min. Care was taken so that the gripping pressure and the specimen alignment were repeatable and to avoid slippage or breakage at or near the jaws. A material testing software program, Bluehill 2, was used to correct for any preloading or pretension force experienced by the fabrics once the grips were in place and to capture the results of the test. Changes in the yield load (YL), tensile extension (TE), load at break (LB), tensile strength (TS) and the tensile modulus (TM) before and after each laundry cycle were tested for any alteration in mechanical properties during the laundering regime.

3.3.1 Characterising the load-extension behaviour

The load-extension behaviour of the fabrics after each laundry cycle was examined by plotting the load versus the change in extension from experimental gauge length (125mm). The load-extension curve of the fabrics (Figure 3.8) was constructed from the data obtained from the tensile test described in Section 3.3. The curve shows typical behaviour of PLA, PET before and after laundry divided into three stages, and cotton divided into two.

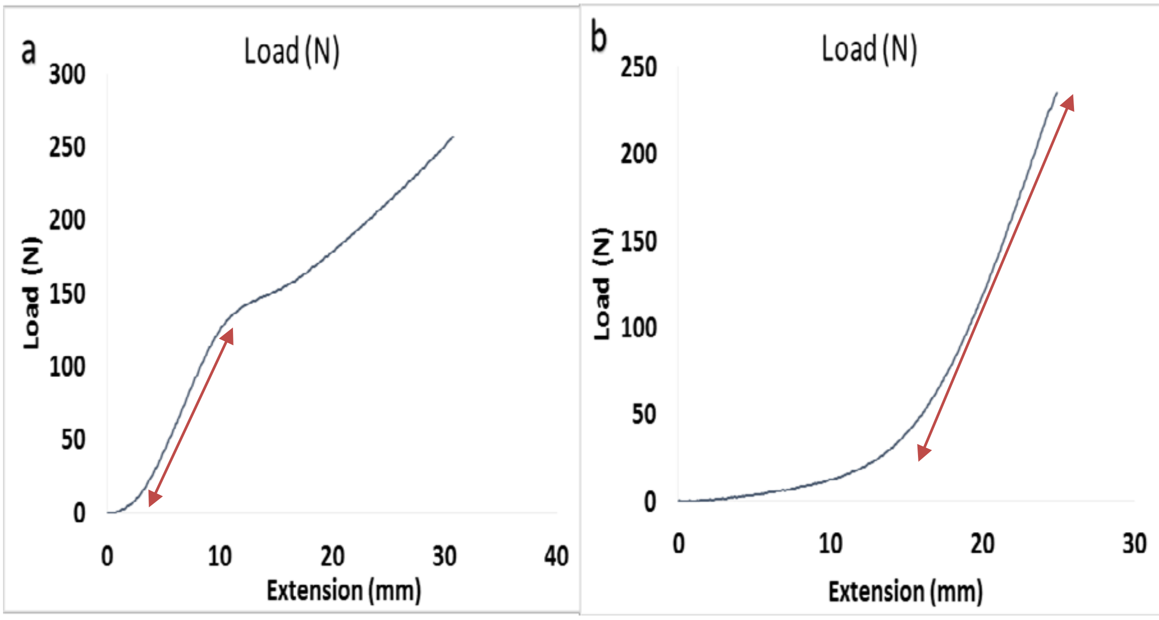

Figure 3.8: Example of load-extension curve of (a) PLA and PET and (b) cotton (Source: Author)

It was observed that as the specimens were loaded and pulled in the test direction (warp), adjacent yarns try to straighten out or rotate to accommodate the shifting and crimping in the fabric. Crimping in the fabric leads to a phenomenon called fibre cohesion (Lewin 2007) causing yarns to cling together.

Based on Hooke's law, under the low extension, the behaviour of fabrics are linearly elastic (Idumah *et al.* 2013). However, as the extension increases and exceeds the limit (yield point); the material loses its linearity and attains a viscoelastic extension, which may not be recoverable depending on the type of fabric. At the start of the load-extension analysis, the smallest load triggers an inter-yarn deformation in the fabric fibres and positions them in the direction of the load. The behaviour of the fabrics at this point relates to the extension before the linear elasticity of the material begins. Also, the behaviour and possible durability of the fabric after each laundry cycle relate to the type of laundry treatments subjected to and the shape of the linear elastic portion of the curve before the yield point.

Beyond this, the yarns start to lock up thus initiating a rapid rise in the load resistance and a deformation of the fabrics within the linear elastic region of the curve. For PLA and PET, this phenomenon continues until the bending between adjacent yarns reaches a limit as the load applied increases. This indicates the fabric yield point, the boundary between the linear elastic and the viscoelastic region. At the end of this stage, the fully entwined yarns deform such that the fabric could not return to its original state if the applied load was removed. However, if the load applied does not exceed the yield point, the material can return to its initial state (Bothe *et al.* 2013, Klevaityte and Masteikaite 2008, Liu *et al.* 2008). This is fundamental to the quality and durability of the fabric, given that during use and laundering, recovery is the vital parameter that determines the quality of the fabric

3.3.2 Characterising the tensile properties

3.3.2.1 Yield Strength

The yield strength is the stress or load applied to the fabrics samples at which plastic deformation starts to occur. If the load applied does not exceed the yield point, the fabric can return to its original state. This is fundamental to the quality and durability of the fabric, given that during use and laundering, recovery is the vital parameter that determines the quality of the fabrics. After each wash cycle, the yield strength of the samples was determined using the ISO 13934-1 mechanical test standard for “textile tensile properties of fabrics: maximum force and elongation at maximum force using the strip method” and the Instron tensile strength tester (Model 5564). The test was carried out on 25mm by 200mm strips samples cut from each fabric, five with the longer side parallel to the warp. The machine gauge length was set to 125mm and a constant rate of extension (CRE) 100 mm/min.

3.3.2.2 Load at Break

The load required for a fabric sample subjected to a constant rate of extension (CRE) to rupture was also determined using the strip method of the ASTM D5035 standards. The same quantity and size of the sample specimen was clamped to the Instron tensile strength tester (Model 5564) and pulled in a tensile direction parallel to each yarn direction until the fabric breaks. Due to the weave and the properties of the fabrics, the stress due to the load at break is not uniform throughout the specimen, and it only applies to the point at which the specimen breaks.

3.3.2.3 Tensile Strength

The tensile strength of the fabric is a measure of the actual force required to break the samples. This is different from the maximum force that the material can withstand or support. In other words, the strength of the fabric determines the force required to break it when under tension. The breaking strength of the fabric differs with types, weave, the yarn count and anisotropy. During the use phase, repeated laundry processes plays a significant role in the breaking strength of fabrics. Consequently, the variation in the breaking strength over the selected laundry regime (unwashed, 1, 3, 6, 10, 30, and 50 cycles) was taken into consideration to determine and compare the significance of the wash cycle of the three fabrics.

The tensile breaking strength experiments for the fabric specimens were carried out on the Instron tensile tester using the strip method of the ASTM D5035 standards. After each laundry cycle, the tensile breaking strength was determined from the breaking load using the equation:

$$\sigma = Load\ at\ break / A$$

Equation 1

Where:
σ= breaking strength MPa

Load at break = Breaking Load, N

A = Cross sectional area, m^2

3.3.2.4 Tensile Extension

The tensile extension was evaluated by measuring the change in the length of the sample after loading. The distance (gauge length) between the clamps or the grips on the Instron tensile tester was set at 125 ± 1 mm. During the tensile test, the specimen was pulled at a continuous increasing extension and a load that was longitudinal to the test specimens. The result of the increase in gauge length during loading determined from the recorded load-extension curve at the breaking load and captured by the Instron Bluehill software. The tensile extension, which is the percentage ratio of the increase in the gauge length to the gauge length before the stretching, was determined using equation 2:

$$\%\boldsymbol{E} = \left(\frac{\textbf{Extension }(\mathbf{E}\boldsymbol{x})}{\textbf{Guage Length}}\right)\textbf{ x 100}$$

Equation 2

Where:
%E = Tensile Extension
Ex = Extension
Gauge Length = Distance between the grips
$\boldsymbol{x}$ = Number of washing cycle from 0, 1, 3, 6, 10, 30, 50

3.3.2.5 Tensile Modulus

The tensile modulus of elasticity is a measure of the stiffness of the fabric calculated at the linear zone of the stress–strain curve produced during the test. As the load is applied to the specimen and extension begins to occur, the stress experienced varies across the surface of the specimen due a scratch, incision or other defect produced during laundry and tumble-drying. As a result, the modulus of elasticity can be determined as the angle of the tangent of the slope of the linear portion of the stress-strain curve.

For the polyethylene terephthalate and polylactic acid fabric, the elastic modulus was determined at the E2 stage (Figure 3.8a). If the load were to stop at this point, the material will exhibit its elastic properties and recover to its original state (9). For the cotton fabric, the elastic modulus was determined from the linear part of the the curve of the second stage (Figure 3.8b). By definition:

$$E = \frac{\sigma}{\varepsilon} = \frac{\mathrm{F}/(\mathrm{t}*\mathrm{b})}{\Delta\mathrm{l}/\mathrm{l}}$$

Equation 3

Where:
t= Thickness of the fabric
l = gauge length of the specimen
b= width of the specimen

F= max load reached
σ = Stress
ε = Strain
Δl= change in the gauge length due to loading

3.4 Statistical Analysis

Statistical analysis was performed using SPSS 20, to validate the result of the load-extension behaviour and to investigate the significance of fabric type, laundry cycles and laundry treatment as factors on the tensile properties of the fabrics. Using a univariate analysis of variance (ANOVA) and a regression analysis, a descriptive statistics (mean of five samples) standard deviation (sd) and coefficient of variance (CV %) was calculated for percentage extension (TE), load at break (LB), tensile strength (TS) and the tensile modulus (TM).

The factors were considered significant at a *p*-value of less than 0.05. Also, a Tukey post hoc pairwise comparison was used to evaluate and compare the mean difference between each laundry cycle and the unwashed fabric. Table 3.3 shows the three between-subjects independent variables and the levels (n); wash cycle (n=6), fabric type (n=3) and the laundry treatments (n=4) and a number of observations used for the analysis.

Table 3-3: Between subject factor for statistical analysis

	Levels (n)	Value Label	No of observations
Laundry Cycle Regimes	0	Unwashed	30
	1	One laundry cycles	30
	3	Three laundry cycles	30
	6	Six laundry cycles	30
	10	Ten laundry cycles	30
	30	30 laundry cycles	30
	50	50 laundry cycles	30
Fabric Type	1	PLA	60
	2	PET	60
	3	COTTON	60
Laundry Treatments	Detergent/tumble-dried (DT), detergent air-dried (DA), detergent/softener/tumble-dried (DST) and Detergent/softener/air-dried (DSA).		

3.5 Life Cycle Assessment (LCA)

The life cycle assessment model was created using GaBi 4 software developed by PE International. The assessment analyses the environmental impact of production through the wash cycles that represent the end of use for each fabric. The purpose is to assess the contribution of products and services to impact category such as; greenhouse gas emission (GHG), water resources usage and the potential energy demand (PED). The entire life cycle assessment, methods, inventory and analysis are presented in Chapter 5 of this thesis.

4 RESULTS

4.1 Introduction

This chapter presents the data and results of the laundry-durability experiment carried out on the fabrics studied. The results show the influence of different laundry regimes and treatments on the lifecycle of PLA, PET and cotton fabrics from both pilot and the actual research. Following the repeated laundry regime described in Chapter 3, the results were analysed by:

i. Plotting and comparing the load-extension profile after the wash programme for each fabric
ii. Plotting and comparing the load-extension profile of each fabric under different laundry treatments
iii. Evaluating the tensile properties: load at break, tensile modulus, extension for PLA, PET and cotton fabric after each laundry regime and treatments
iv. Using the SPSS Statistics 20 software to analyse the influence of the laundry regime and laundry treatment (i.e. with or without fabric softener and different drying conditions) on PLA, PET and cotton fabrics.

The limit between the elastic region and the viscoelastic region where the material ruptures (yield load), extension at yield load were used to illustrate the behaviour of the fabrics during laundry regime. Changes in tensile properties of the material were used to characterise the influence of progressive laundry regime and laundry conditions. The aim is to compare the different laundry programmes, fabric to fabric, and to distinguish which laundry cycle during the regime showed significant alteration compared to the original unwashed fabrics. The tensile experiment was carried out under the assumption that all constituent yarns are made from the same fibres, are perfectly elastic and have circular cross sections.

4.2 Pilot experiment: comparative influence of laundry use phase on deformation behaviour of PLA, PET, and cotton fabric

During the pilot experiment, it was observed that as the specimens were loaded and pulled in the test direction (warp), adjacent yarns tried to straighten out or rotate to accommodate the shifting and crimping in the fabric. Crimping in the fabric leads to a phenomenon called fibre cohesion (Lewin 2007) causing yarns to cling together.

4.2.1 Pilot Experiment: Load-extension Profile

Figures 4.1 and 4.2 illustrates the load-extension curve for five replicate fabric specimens and show the different stages of extension the fabric experiences during loading. Assuming the yarn diameter throughout the fabric remains constant; the general load-extension curve analysis revealed two stages for the cotton fabric while PET and PLA behaved in the same way: showing three stages E1, E2 and E3.

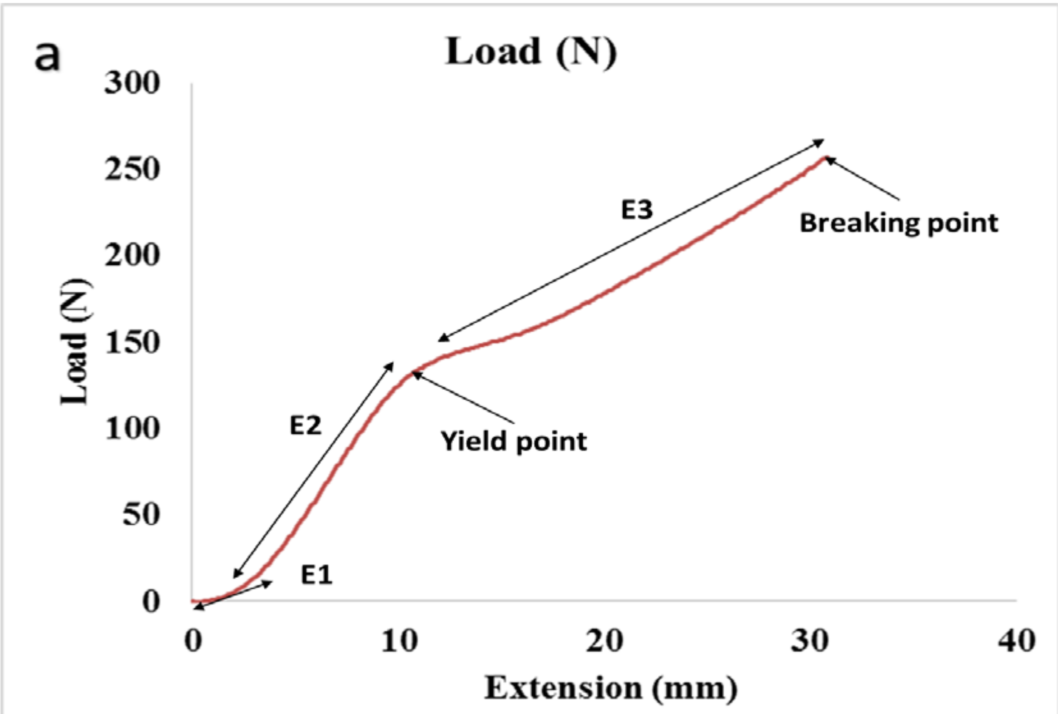

Figure 4.1: Example of load-extension curve for PET and PLA fabric showing three stages of tension and extension

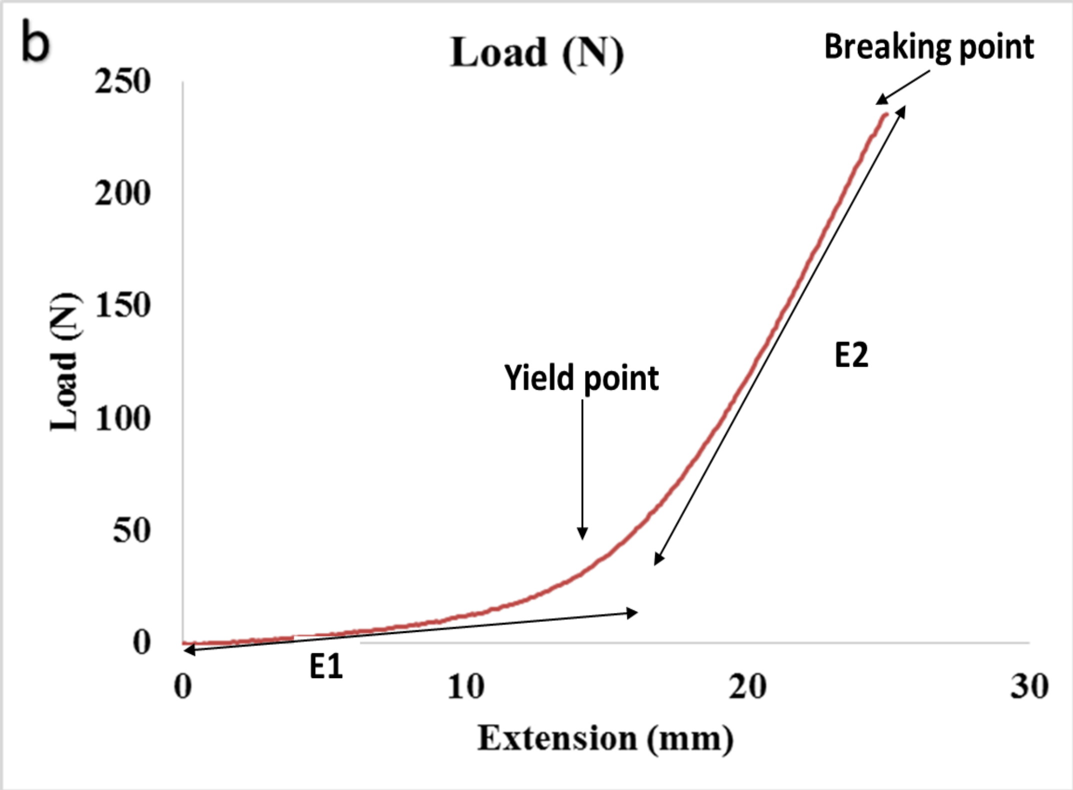

Figure 4.2: Example of load-extension curve for cotton fabric showing two stages of tension and extension

The initial portion of the curve (E1) for both Figures 4.1 and 4.2 shows a non-linear profile, caused by resistance to bending or crimping of the constituent fibre yarns in the transverse direction of the applied load. This stage starts rapidly producing a friction between the yarns in the direction of load and the perpendicular yarn as they are straightened and rearranged under a small load (between applied forces of 0.01 to 1 N, which is not proportional to the extension (up to 1.5 mm). For this analysis, this part of the curve is not relevant due to small tensile modulus resulting from the initial inter-fibre, inter-yarn friction and the decrimping of adjacent yarns.

Based on Hooke’s law, under the low extension, the behaviour of fabrics are linearly elastic (Idumah *et al.* 2013). However, as the extension increases and exceeds the limit (yield point) the fabric loses its linearity and attains a viscoelastic extension, which may not be recoverable depending on the type of fabric. At the start of the load-extension analysis, the smallest load triggers an inter-yarn deformation in the fabric fibres and positions them in the direction of the load. The behaviour of the fabrics at this point relates to the extension before the linear elasticity of the fabric begins. In addition, the behaviour and possible durability of the fabric after each laundry cycle relates to the type of laundry treatments it is subjected to and the shape of the linear elastic portion of the curve before the yield point.

Beyond this, the yarns start to lock up thus initiating a rapid rise in the load resistance and a deformation of the fabrics within the linear elastic region of the curve. For PLA and PET, this phenomenon continues until the bending between adjacent yarns reaches a limit as the load applied increases. This indicates the fabric yield point, the limit between the linear elastic and the viscoelastic region. At the end of this stage, the fully entwined yarns deform such that the fabric could not return to its original state if the applied load was removed. However, if the load applied does not exceed the yield point, the fabric can return to its initial state (Bothe *et al.* 2013, Klevaityte and Masteikaite 2008, Liu *et al.* 2008). This is fundamental to the quality and durability of the fabric, given that during use and laundering, recovery is the vital parameter that determines the quality of the fabric.

4.2.2 Pilot Experiment: Investigating the load-extension performance of PLA, PET and Cotton fabric during laundry

Figures 4.3a-c show the load-extension behaviour of PLA, PET and cotton fabrics for unwashed fabric, one, 10 and 50 laundry cycles. The difference in shape, the yield load and extension of the linear elastic region was used to explain the fabric behaviour during laundry regime. As revealed in Figure 4.3a, the most important behaviour of the PLA and PET fabrics is distributed in two main portions, the elastic region and viscoelastic region. However as explained later (Section 5.3), the initial behaviour of the fabric involves a slipping of adjacent yarns as they became aligned more quickly with the load direction under low 10 N loads (4.2% stress) and extension between 1-2 mm (1.6% strain) for PLA and 3 mm (2.4% strain) for PET.

In contrast, the load-extension curve for cotton exhibited a slightly concave profile inclining towards the extension axis. The behaviour also showed two portions of the load-extension curve: the initial alignment and yarn lockup, which is similar to PET and PLA at low load but a higher extension of 14 -15 mm (12% strain) and the linear elastic region. At the end of this stage, the fabric ruptures without displaying any clear yield point. The parameters considered at this point are fundamental to the quality and durability of the cotton fabric. A summary of statistics on the yield load and extension at yield for PLA, PET and cotton by laundry treatment and number of laundry cycles is given in Appendix 9 and 10.

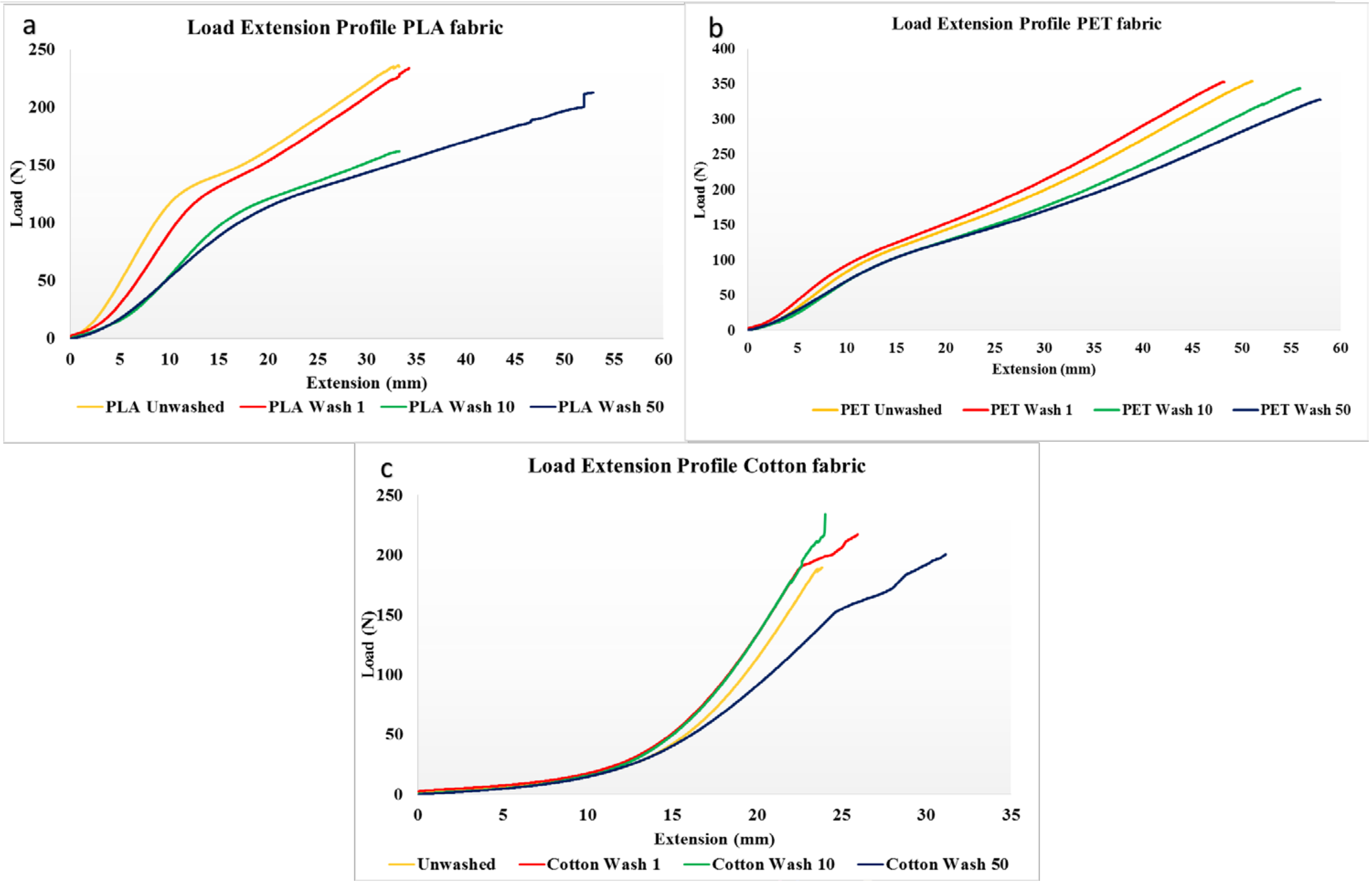

Figure 4.3: Influence of pilot laundry and tumble treatments on (a) PLA, (b) PET and (c) Cotton fabrics 1, 10 and 50 laundry cycles

The behaviour of the unwashed fabrics at the yield load showed a higher yield load of 189.42 N and extension 23.85 mm for cotton (Figure 4.3c) followed by PLA (Figure 4.3a) at 125.48 N and extension 11.15 mm and PET (Figure 4.3b) at 100.82 N and extension 12.27 mm. PLA fabric showed a higher yield load within a small extension compared to PET, which showed a lower yield load with almost similar extension.

Compared to the unwashed fabrics, the yield load after one laundry cycle showed an increase of 4% for cotton fabric, however for PLA, there was a 5% reduction in yield load but an extension increase by 4%. PET fabric, on the other hand, showed a 2% and 13% decrease in the yield load and extension. Despite this difference in behaviour after one laundry cycle, there seems to be an overlap in the load-extension curves as PLA tends towards the PET. It was also observed that the PLA and cotton fabrics exhibited similar extension after one laundry cycle.

The result in Figure 4.3a shows that the behaviour of PLA exhibited a gradual rise in the load resistance after 10 wash cycles until an extension of 5-6 mm after which the resistance to loading increased. At the yield point, it was found that, at a 50% stress under 120 N load the unwashed PLA experienced a strain of 7.6% and extension of about 9-10.5mm; however after 10 wash cycles, the strain increased to 13% at a 16mm extension under a lower 42% stress and 100 N load.

After 50 wash cycles, the fabric behaved similarly to the 10 laundry cycle. This suggests that the most significant laundry durability of PLA lies within the first 10 laundry cycles, it then stabilises and behaves in the same way, even after 50 wash cycles.

In comparison, the deformation behaviour of the PET (Figure 4.3b) after 50 wash cycles was not different from the unwashed fabric. The alignment and yarn lockup upon initial loading occurred at about 3mm (2.4% strain) extension for all samples after each wash cycle. The resistance to load is increased until a yield point of 10-11.3 mm extension (8% strain), 80N load (22% stress) for the unwashed fabric and 12mm extension (9.6%), and about 90N load (26% stress) for the 10-50 wash cycles. The small difference in the yield points shows a slight but steady influence of the wash cycles on PET fabric.

The deformation behaviour of cotton fabric showed an alignment and yarn lock up at about 14.5-15mm (12% strain) extension after which a rapid rise in the load resistance occurred within the elastic region of the curve. After yarn lockup, the force experienced by the fabric shows a rapid increase at 10 wash cycles followed by the unwashed fabric and 50 washes. The load-extension profile after 10 wash cycles showed a higher stiffness, hence the 10% increase in the modulus. This is due to the swelling of cotton fibres from absorption of water during washing, resulting in increasing friction between the yarns and increased resistance to loading within a small extension. The result in Figure 4.3c shows that the yielding and rupture of the cotton fabric occurred at the same time, load, 160-190 N (16-20%) and extension (20-25mm). This can be attributed to the 97% cellulose polymer components of cotton fabric that enables it to form hydrogen bonds between adjacent –OH groups. On impact with the water, the molecules bond to the –OH, resulting in a swelling of the constituent yarns and consequently, the shrinking of cotton fabric. The shrinking limits any internal chain mobility within the fabric (Wakelyn *et al.* 2006), thereby causing resistance to any applied load.

4.2.3 Pilot Experiment: Tensile Properties

4.2.3.1 Percentage Extension at Break

Figure 4.4 shows that, for unwashed fabric, the extension is higher in PET (43%) than PLA (28%) and cotton (23%). This closely agrees with the dry breaking extension, 20-35% for PLA and 20-50% for PET and 7-10% for cotton as reported by Zupin and Dimitrovski (2010).

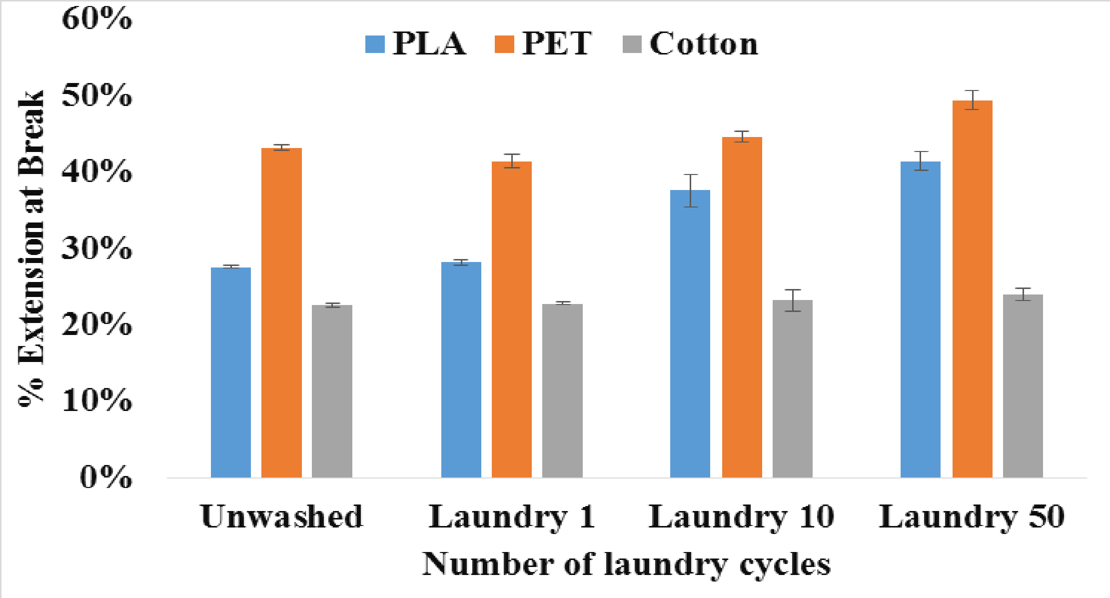

Figure 4.4: Effect of laundering regime on the breaking extension (%) of PLA, PET and cotton fabric across a range of laundry cycles. Error bars: 95% CI

The results also indicated that as the laundry cycle increased the percentage extension for PLA increased significantly after 50 laundry cycles compared to PET. Cotton fabric, however, remained steady. PLA fabric showed a 28% extension for the unwashed fabric which did not change after one laundry cycle. This can be attributed to the excellent wicking property of PLA, which allows it to draw up without absorbing a significant amount of water (Avinc and Khoddami 2009). For the unwashed fabrics, there was a 16% difference in extension between PLA and PET, which remained consistent after one laundry cycle. However, with increasing laundry, the percentage extension for PLA seems to increase by 10% after 10 laundry cycles, which was only 7% less than PET.

After 50 laundry cycles, PLA increased by 13%, which was 8% less than PET. Although an increase in extension occurred with increasing laundry in both fabrics, PLA appeared to exhibit a higher extension. This suggests that PLA fabrics exhibit superior flexibility and softness qualities that are further enhanced by the laundry process. The high crystallinity, hydrophobic properties and its inability to swell significantly during laundry as reported by Agarwal *et al.* (2011d) could be the reason for this.

4.2.3.2 Tensile Modulus

Figure 4.5 compares the tensile modulus of PLA, PET and cotton fabric after 50 laundry cycles. The results show a high tensile modulus (20.5 MPa) of unwashed cotton, compared to 13.9 MPa of PLA and 10 MPa of PET fabric. This confirms the results from literature such as Kononova *et al.* (2011) and Williams (2010) which reported that cotton fabric exhibits very high tensile modulus; 5-12 MPa compared to 2-4 MPa for PET (Raftoyiannis 2012).

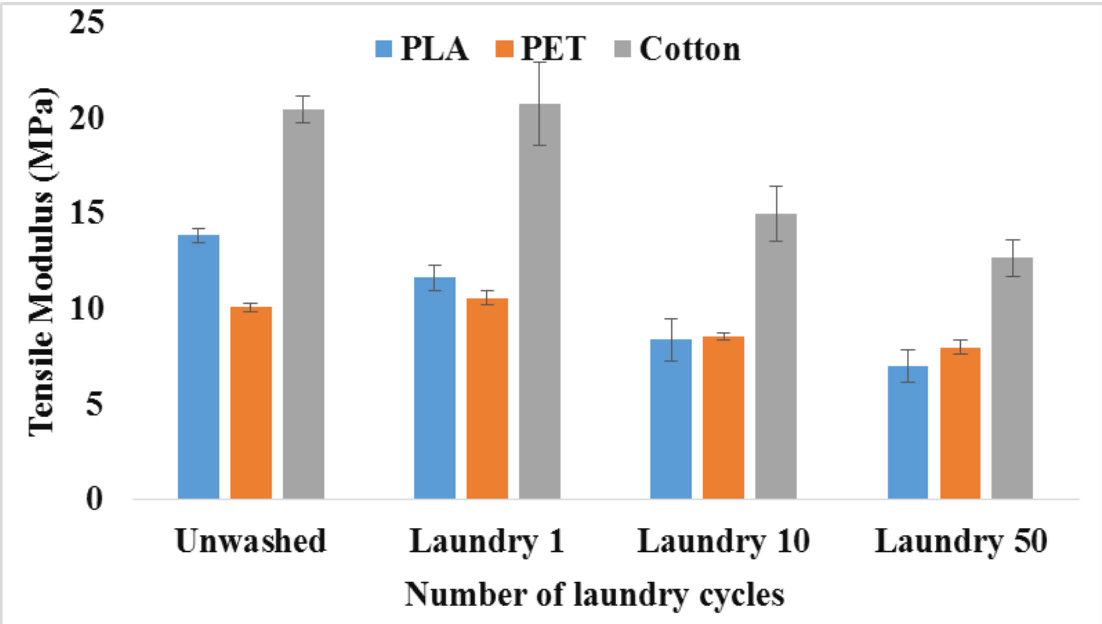

Figure 4.5: Effect of laundering regime on the tensile modulus of PLA, PET and cotton fabric across a range of laundry cycles. Error bars: 95% CI, n=5

However, the result shows a general decline in the tensile modulus of the fabrics with increasing laundry cycles; the effect was more pronounced on PLA fabric. After one laundry cycle, the tensile modulus for PLA reduced from 13.9 MPa for the unwashed fabric to 11.6 MPa, whereas, PET and cotton showed a slight increase of 0.5 MPa and 0.3 MPa respectively. With increasing laundry, PLA continued to decrease to 8.4 MPa after 10 laundry cycles, and then slightly to 7.0 MPa after 50 laundry cycles. The tensile modulus reduced by 13%, 8% and 4% for PLA, cotton and PET respectively after 10 laundry cycles. After 50 laundry cycles, the tensile modulus decreased by 17% for PLA, 11% for cotton and 6% for PET compared to the unwashed fabric. This decrease may be attributed to the high 60^{o}C tumbled drying temperature. The results show that the laundry regime had a pronounced effect on the tensile modulus of PLA fabric between the first and tenth wash.

4.2.3.3 Tensile Strength

The effect of laundry on the fabrics, as shown in Figure 4.6, indicates a general decline in the tensile strength. This was, however, more prominent in PLA fabric compared to cotton and PET.

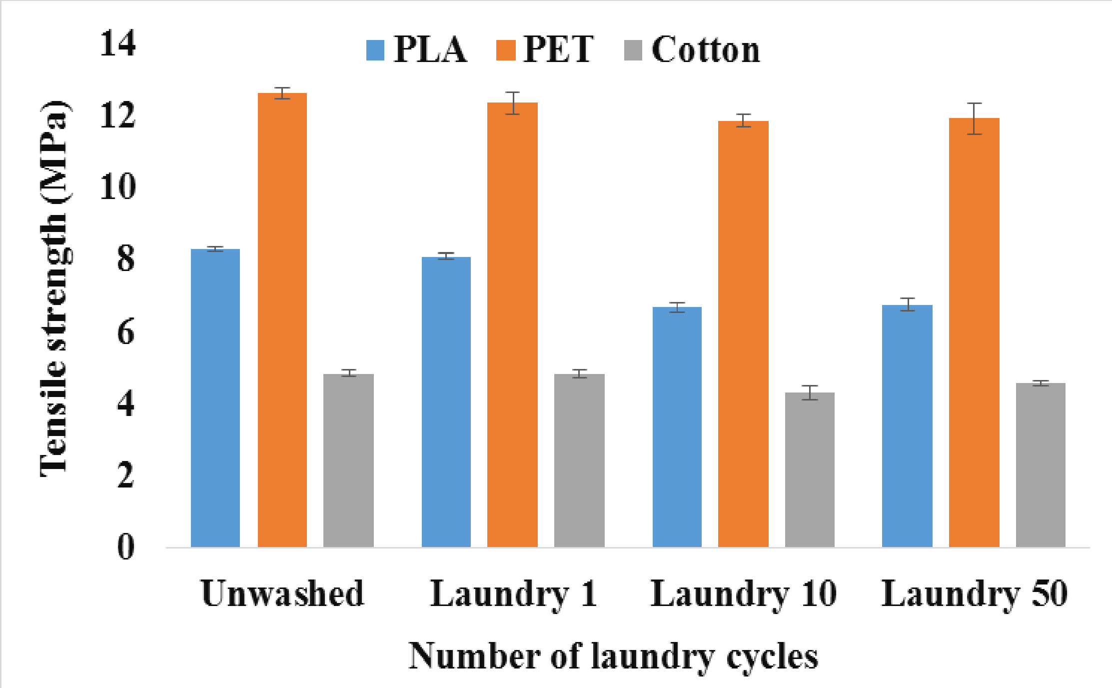

Figure 4.6: Effect of laundering regime on the tensile strength of PLA, PET and cotton fabric across a range of laundry cycles. Error bars: 95% CI, n=5

The result revealed that, with increasing laundry, the tensile strength of PET fabric decreased slightly from 12.6 MPa (for unwashed fabric) to 12.3 MPa (after one laundry cycle) and 11.9 MPa (after laundry 10), then remained steady up to 50 laundry cycles. For PLA fabric, the tensile modulus decreased slightly from 8.3 MPa for the unwashed fabric to 8.1 MPa after one laundry cycle, then decreased by 20% after laundry 10 and stayed the same up to 50 laundry cycles. On the other hand, cotton fabric showed no sign of changes in the unwashed fabric (4.9 MPa) and one laundry cycle (4.8 MPa), but decreased slightly to 4.3 MPa after laundry 10 and then increased to 4.6 MPa after 50 laundry cycles.

4.3 Investigation of the influence of laundry cycles on the performance of PLA, PET and cotton fabrics after different laundry treatments

Using the yield load of load-extension curves, which is the limit between the linear elastic and viscoelastic region, the influence of different laundry conditions on the fabric types were compared. The laundry conditions characterised are detergent/tumble-dried (DT), detergent air-dried (DA), detergent/softener/tumble-dried (DST) and Detergent/Softener/air-dried (DSA).

4.3.1 Polylactic acid fabric

Figures 4.7a-d show the load-extension curve of PLA fabrics subjected to the different laundry treatments after 50 laundry cycles. Figure 4.7 (a) and (c), shows a distinct variance in the extension, between 1-5 mm for DT and 3-7 mm for DST fabric after each laundry cycle. The only difference between (a) and (c) is the softener treatment used in (c). This suggests that, regardless of the use of fabric softener, tumble-drying has an adverse effect on PLA fabric. As illustrated in Figure 4.7 (a) and (c), the linear elastic portion and yield point of the DT, and DST curves are distributed out over a range of extension. However, between the unwashed fabric and 10 laundry cycles, the linear elastic portion and yield load on the detergent/softener and tumble-dried curves (Figure 4.7) are collected together at the same point. This suggests that softeners helped to lessen the effect of laundry on the PLA fabric within the first 10 laundry cycles, regardless of tumble-drying. In contrast, the PLA fabrics washed in DA (Figure 4.7b), and DSA (Figure 4.7d) showed similar behaviour as reflected by the slight variance in the shape of the curves and the yield points. It is evident from Figure 4.7d that the use of fabric softener preserved the performance of PLA fabric after the 50 laundry cycles.

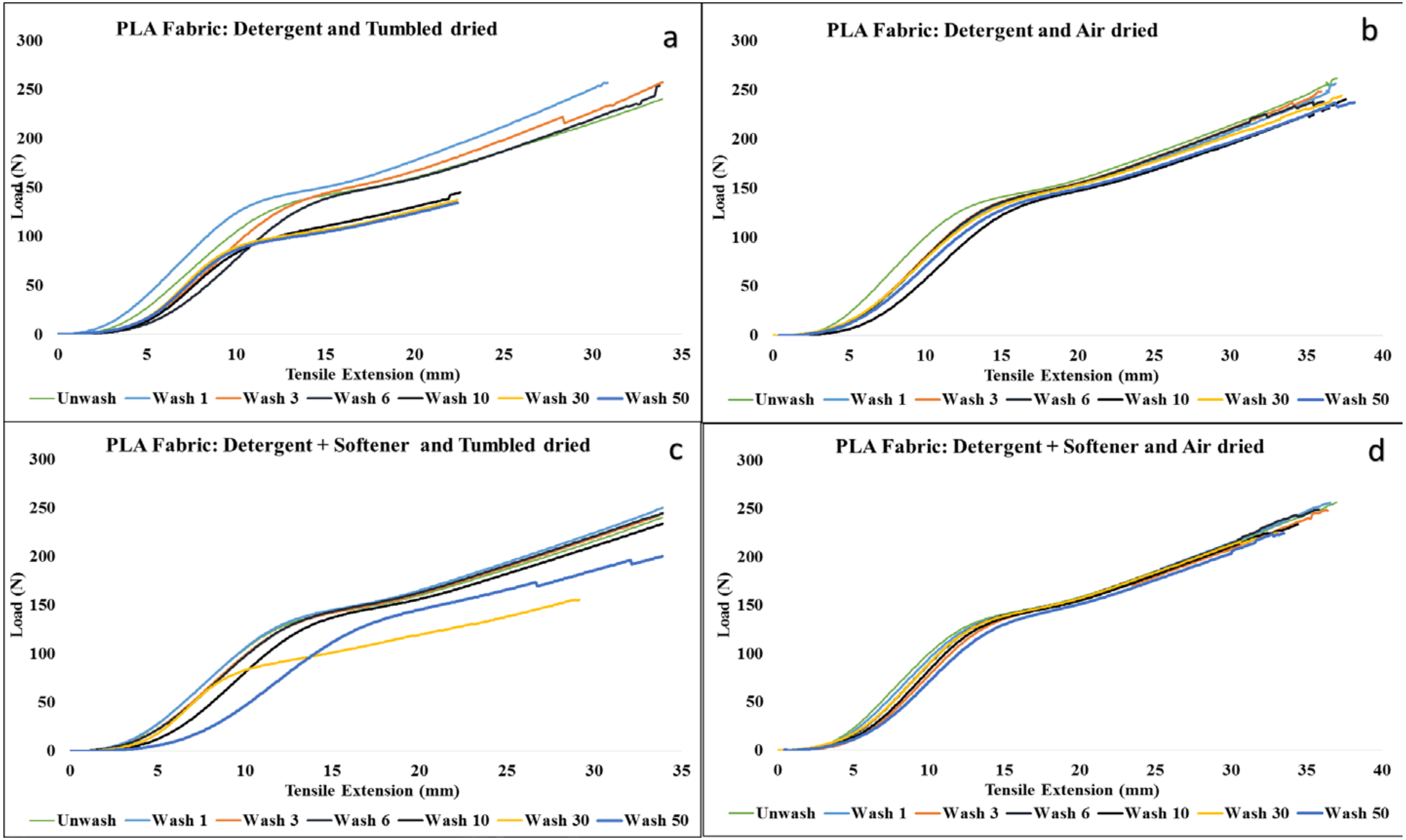

Figure 4.7: Influence of 1,3,6,10,30 and 50 laundry regime on PLA fabric after: (a) detergent/tumble-drying (DT), (b) detergent/air-drying (DA), (c) detergent/softener/tumble drying (DST) and (d) detergent/softener/air-drying (DSA)

4.3.2 Polyethylene terephthalate fabric (PET)

Figures 4.8a-d show the load-extension curve of PET fabrics subjected to the different laundry treatments after 50 laundry cycles. The analysis of the behaviour of the linear portion of the curve and the yield point suggest that, regardless of the number of laundry cycles and treatments, PET fabric behaves similarly. This is reflected in the shape of the load-extension curves for fabrics washed in both DST and the DA.

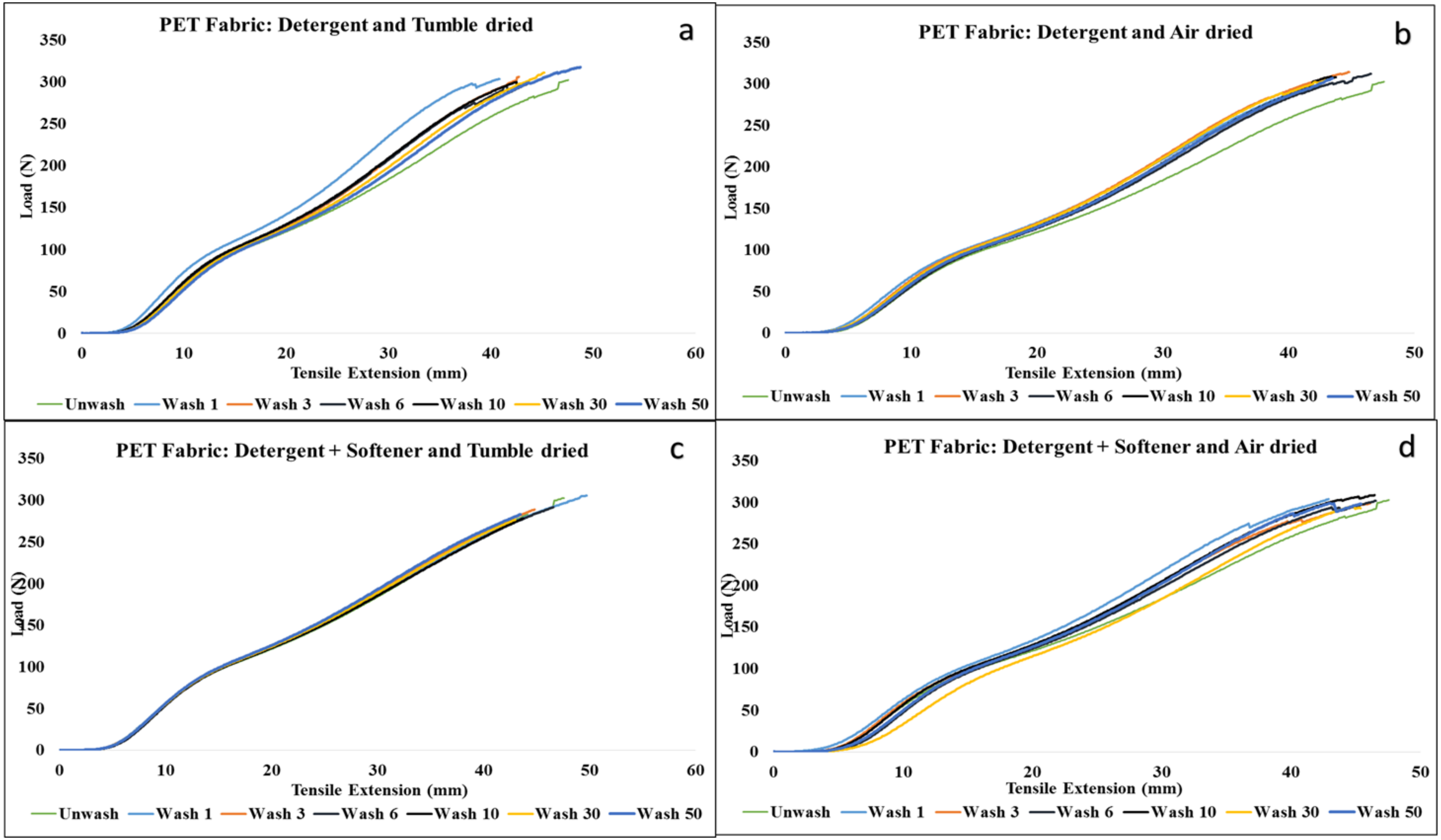

Figure 4.8: Influence of 1,3,6,10,30 and 50 laundry regime on PET fabric after: (a) detergent/tumble-drying (DT), (b) detergent/air-drying (DA), (c) detergent/softener/tumble drying (DST) and (d) detergent/softener/air-drying (DSA)

4.3.3 Cotton fabric

Figures 4.9a-d show the load-extension curve of cotton fabrics subjected to the different laundry treatments after 50 laundry cycles. The impact of the various treatments after 50 laundry cycles is very distinct as reflected in the dissimilar shape of the load-extension curves. Figure 4.9a and 5.9c shows a separate variance in the extension of the linear elastic region of the curves between 14-23 mm for DT and 13-26 mm for DST. However, the shape of the curves for laundry cycles 3 and 6, 10 and 30 are similar, for the fabrics washed in DT. The linear elastic portion and the breaking points show a distinguishing range of extension between 21-33 mm for the DT and 20-38 mm for the DST. The load at the break for the DT fabric remained the same between one and 50 laundry cycles; however, it declined from 210 N to 175 N for the DST fabrics.

The result in Figures 4.9b and 5.9d show that the extension of the linear elastic region for DA and DSA treatments varied slightly between 16-20mm as reflected by the almost adjoining shape of the load-extension curve. In addition, the close proximity of their breaking points revealed that the linear elastic region of the DA and DSA fabrics behaved similarly after 50 laundry cycles. This also suggests that air-drying seems to preserve the performance of cotton fabric after 50 laundry cycles. Furthermore, the use of fabric softener seems to have the opposite effect on cotton when tumble-dried.

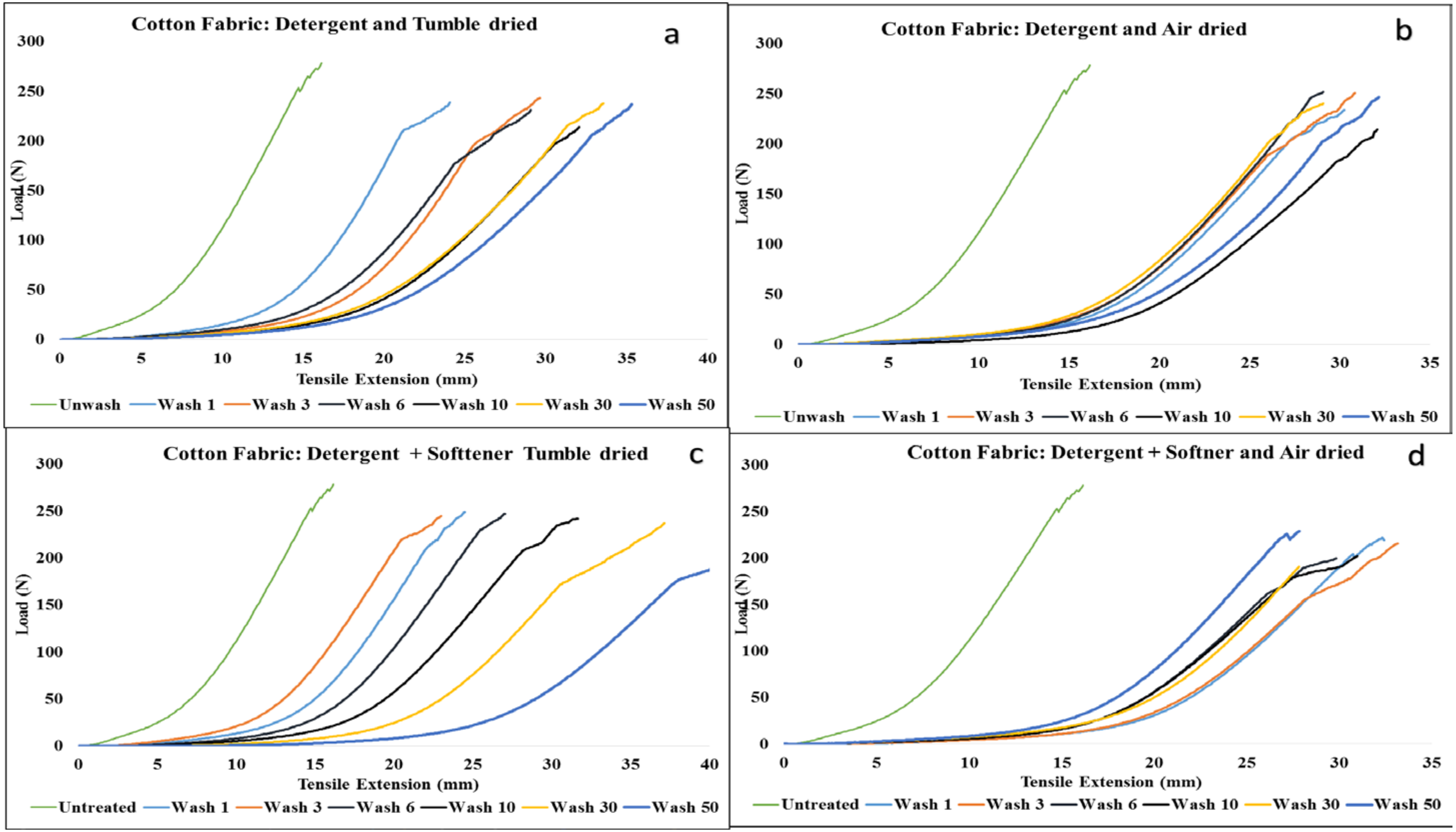

Figure 4.9: Influence of 1,3,6,10,30 and 50 laundry regime on cotton fabric after: (a) detergent/tumble-drying (DT), (b) detergent/air-drying (DA), (c) detergent/softener/tumble drying (DST) and (d) detergent/softener/air-drying (DSA)

4.4 Investigation of the influence of laundry treatments on the performance of PLA, PET, and cotton fabric during laundry cycles

This section compares the effect of laundry regime and different laundry treatments on PLA, PET and cotton fabric after each wash cycle. The objective is to compare the effect of different laundry treatments; detergent/tumble-dried (DT), detergent air-dried (DA), detergent/softener/tumble-dried (DST) and detergent/softener/air-dried (DSA) per laundry cycle on the performance and behaviour of PLA, PET and cotton fabric. The linear elastic region of the load-extension curve is an important phase of any fabric because, if the load applied during testing is removed or does not exceed the limit of this point, the fabric can recover to its original condition. Therefore, this essential parameter determines the quality of the fabrics during wear and laundering lifecycle. The behaviour of the yield point on the load extension and the extension at a yield of the elastic region were characterised and compared between each fabric and laundry cycles. The load-extension behaviour after the laundry regime was compared to the behaviour of the unwashed fabric to estimate the effect of laundry and tumble drying of the fabrics.

4.4.1 Laundry Cycle One

Figures 4.10a-c show the load-extension behaviour of PLA, PET and cotton fabrics after one laundry cycle. From Figure 4.10a, the result shows that PLA exhibited extension between 3-4 mm before the linear elastic region while PET (~5mm) exhibited no variance in the extension for all laundry treatments (Figure 4.10b). However, cotton fabric (Figure 4.10c) exhibited greater extension 6.92 mm, 14.08 mm, 14.25 mm, 18.17 mm and 21.58 mm for the unwashed fabric in the DT, DST, DA and DSA treatments respectively.

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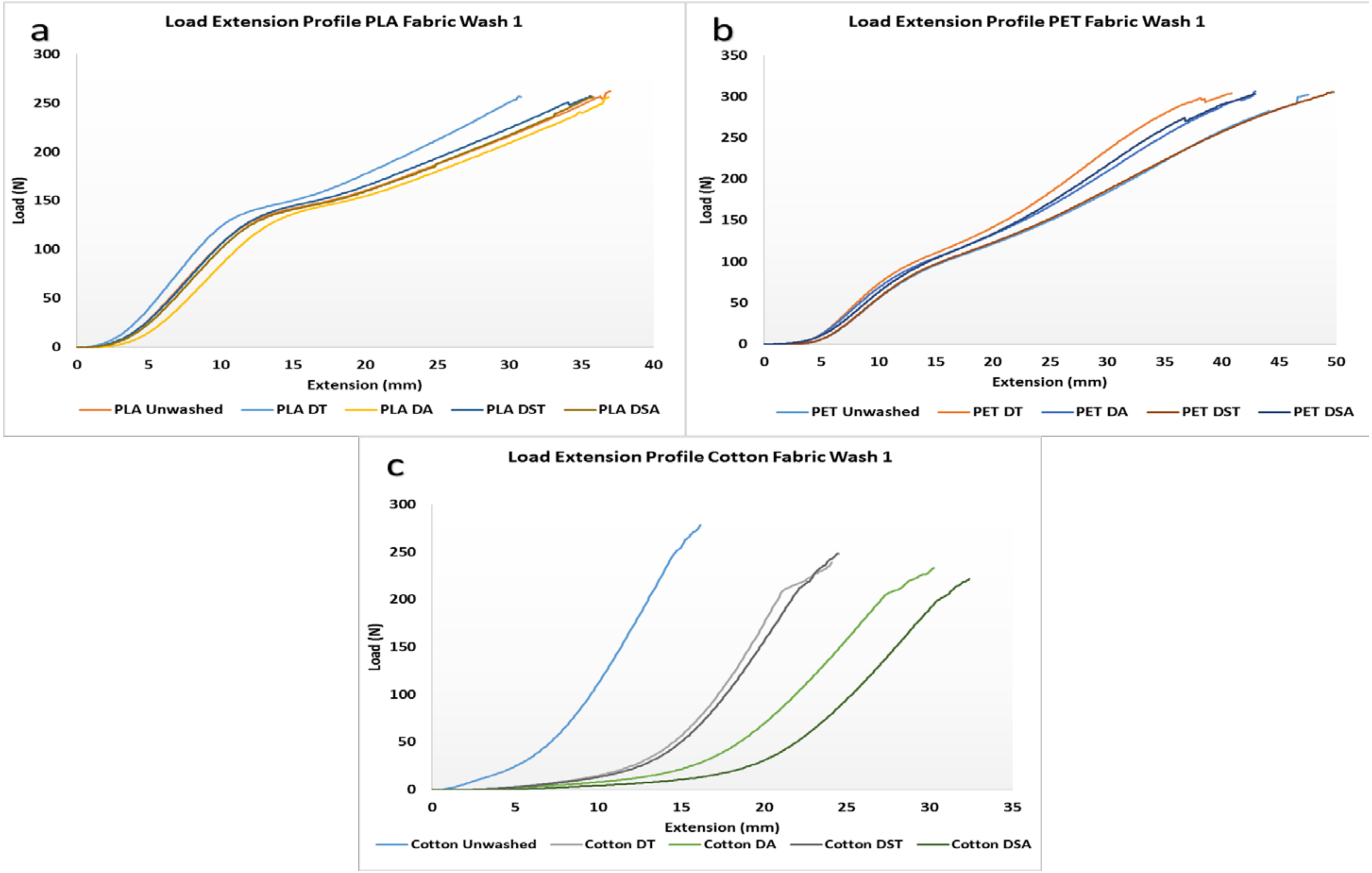

Figure 4.10: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 1 laundry cycle

The behaviour of the linear elastic region is almost similar in shape, except for a slight variation in DST for PLA (Figure 4.10a) and PET (Figure 4.10b) fabrics for all laundry treatments, while cotton seems to show a distinct difference across the laundry treatments (Figure 4.10c). Compared to the unwashed fabric, the influence of the different treatments at one laundry cycle for PLA resulted in a 1% increase in the yield load for DT and 0.4-0.7% increase in DA, DSA and DST. PET showed a similar trend with 1.4% increase in the DT and 1.3% in DA. However, there was no influence of laundry treatments DSA and DST on yield load of the fabrics. On the contrary, the influence of the different treatments on the yield load of cotton after one laundry cycle resulted in a 2.7%, 3%, 3.1% and 4.3% increase in DST, DT, DA and DSA respectively.

4.4.2 Laundry Cycle Three

Figure 4.11a-c shows the load-extension behaviour of PLA, PET and cotton fabrics after three laundry cycles. For all laundry treatments, the fabrics showed similar extension behaviour before the linear elastic region, below 5mm for PLA (Figure 4.11a) while PET (Figure 4.11b) was slightly above 5mm compared to one laundry cycle. Similarly, cotton fabric (Figure 4.11c) exhibited distinct differences in extension of the linear elastic region at 16.83 mm, 12.25 mm, 16.75 mm and 20.58 mm for the DT, DST, DA and DSA treatments respectively at a lower load compared to one laundry cycle.

In Figures 4.11a and 4.11b, the behaviour of the linear elastic region for all laundry treatments was similar in shape for PLA and PET fabric, while cotton seems to show a distinct difference between the laundry treatments (Figure 4.11c). The yield load of PLA behaved similarly for all laundry procedures as reflected by a slight 0.2% increase compared to the unwashed fabric.

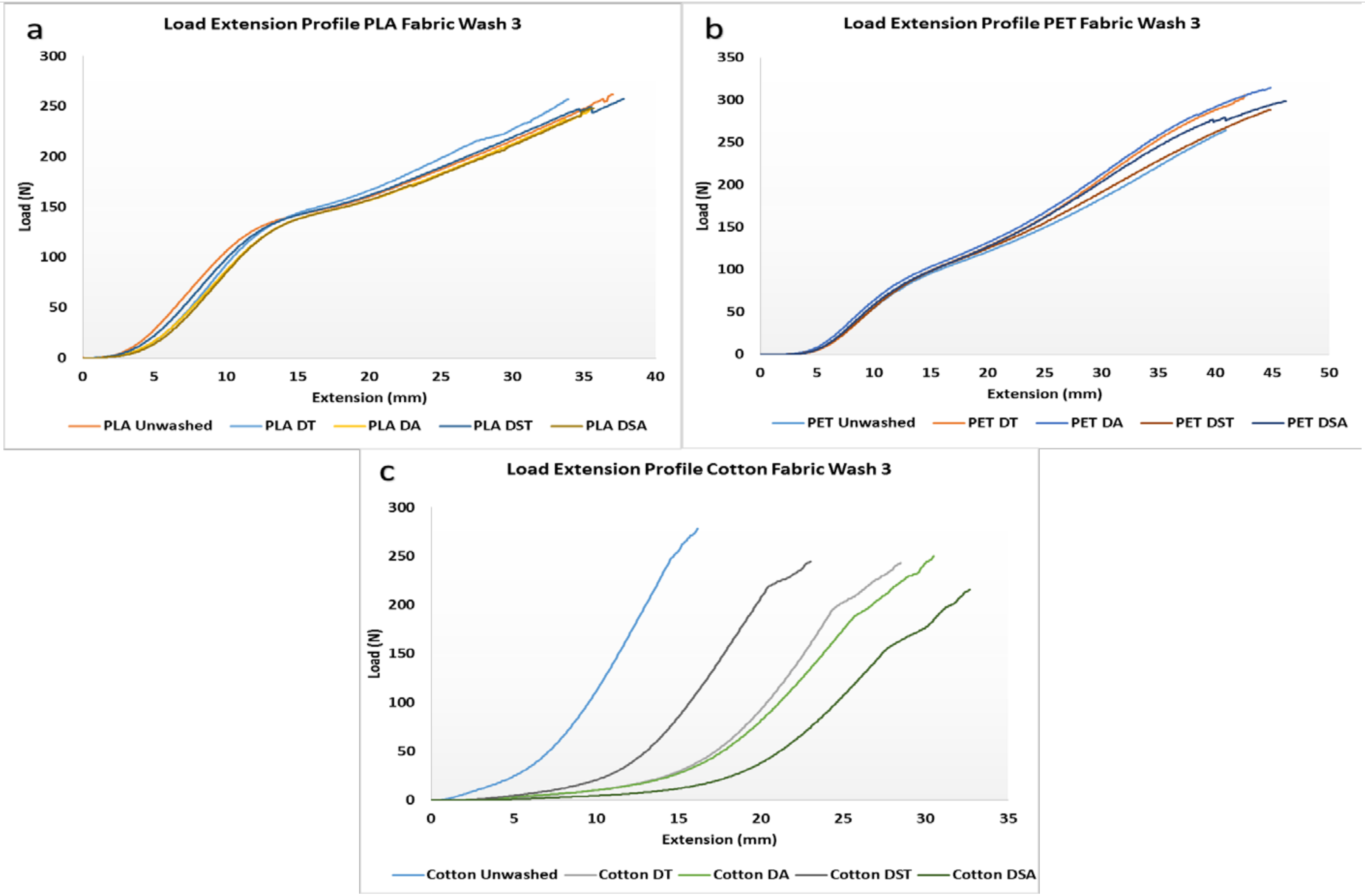

Figure 4.11: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 3 laundry cycles

In addition, PET fabric behaved similarly for all laundry treatments as reflected by the slight 0.2-0.4% increase in yield load for DT, DA and DST, nonetheless, DSA, resulted in a 0.7% reduction compared to the unwashed fabric (Figure 4.11). Similar to one laundry cycle, the influence of different laundry treatments on the yield load at three laundry cycle on cotton fabric resulted in a 2.7%, 3.9%, 4.5% and 7.2% increase in DST, DT, DA and DSA respectively.

4.4.3 Laundry Cycle Six

Figures 4.12a-c demonstrate the load-extension behaviour of PLA, PET and cotton fabrics after six laundry cycles. Like previous laundry cycles, PLA (Figure 4.12a) showed similar extension (below 5mm) behaviour before the linear elastic region, and PET (Figure 4.12b) remained slightly above 5mm across the laundry treatments. However, cotton fabric (Figure 4.12c) exhibited comparable behaviour at similar extensions (between 15.75 -18.17 mm), between the laundry treatments compared to the unwashed fabric.

The result in Figure 4.12a shows consistent behaviour in the shape of load-extension curve and the linear elasticity of PLA, which also reflected in the almost identical yield load for all laundry treatments. However, the extensions at yield load increased slightly and was found to be higher in DT (2.06%), followed by DA (1.58%) while DSA and DST were less than 1%. This suggests that PLA fabric is likely to recover after six laundry cycles and perform similarly to the unwashed fabric regardless of the laundry treatments.

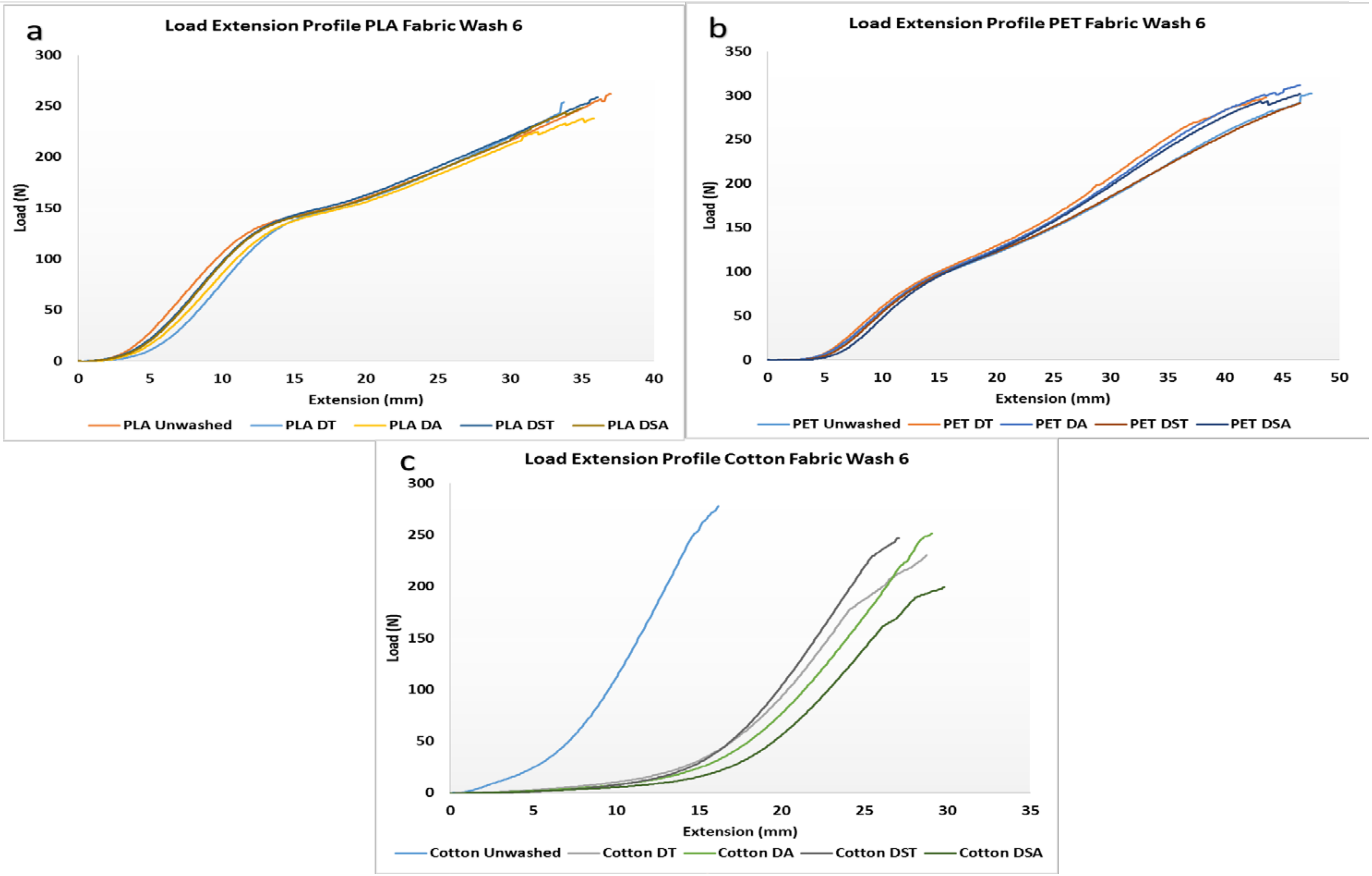

Figure 4.12: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 6 laundry cycles

In Figure 4.12b, the shape of the load-extension curve and the linear elasticity of PET fabric showed similar behaviour, consistent yield load and relative extension at yield for all laundry treatments when compared to the unwashed fabric. For cotton, Figure 4.12c shows that while the difference in the shape of the load-extension curve and linear elasticity persists, there is a steady decline in the yield load of 1.52%, 2.35%, 5.10%, and 6.66% for DST, DA, DT and DSA respectively due to influence of different treatments after 6 laundry cycles. However, the extension at the yield on cotton fabric for all laundry treatments each increased respectively by 5%.

4.4.4 Laundry Cycle 10

Figures 4.13a-c shows the load-extension behaviour of PLA, PET and cotton fabrics after 10 laundry cycles. For all laundry treatments, PET fabrics (Figure 4.13b) showed similar behaviour before the linear elastic region, slightly above 5mm extension. However, for PLA (Figure 4.13a) the extension behaviour before the linear elastic region varied between 3-5mm. Apart from the unwashed fabric, there is no apparent difference in the extension of the linear elastic region for cotton fabric (Figure 4.13c) washed in DT, DST, DA or DSA.

The results in Figure 4.13a suggests that there was a significant influence of the laundry treatments on the shape of the load-extension curve and the disparate slope around the linear elastic region for PLA fabric after 10 laundry cycles. Furthermore, compared to the unwashed fabrics, the laundry treatments resulted in a high (4.29%) reduction for DT while DST, DA or DSA showed less than 1% reduction in yield load with lower (3%) extensions.

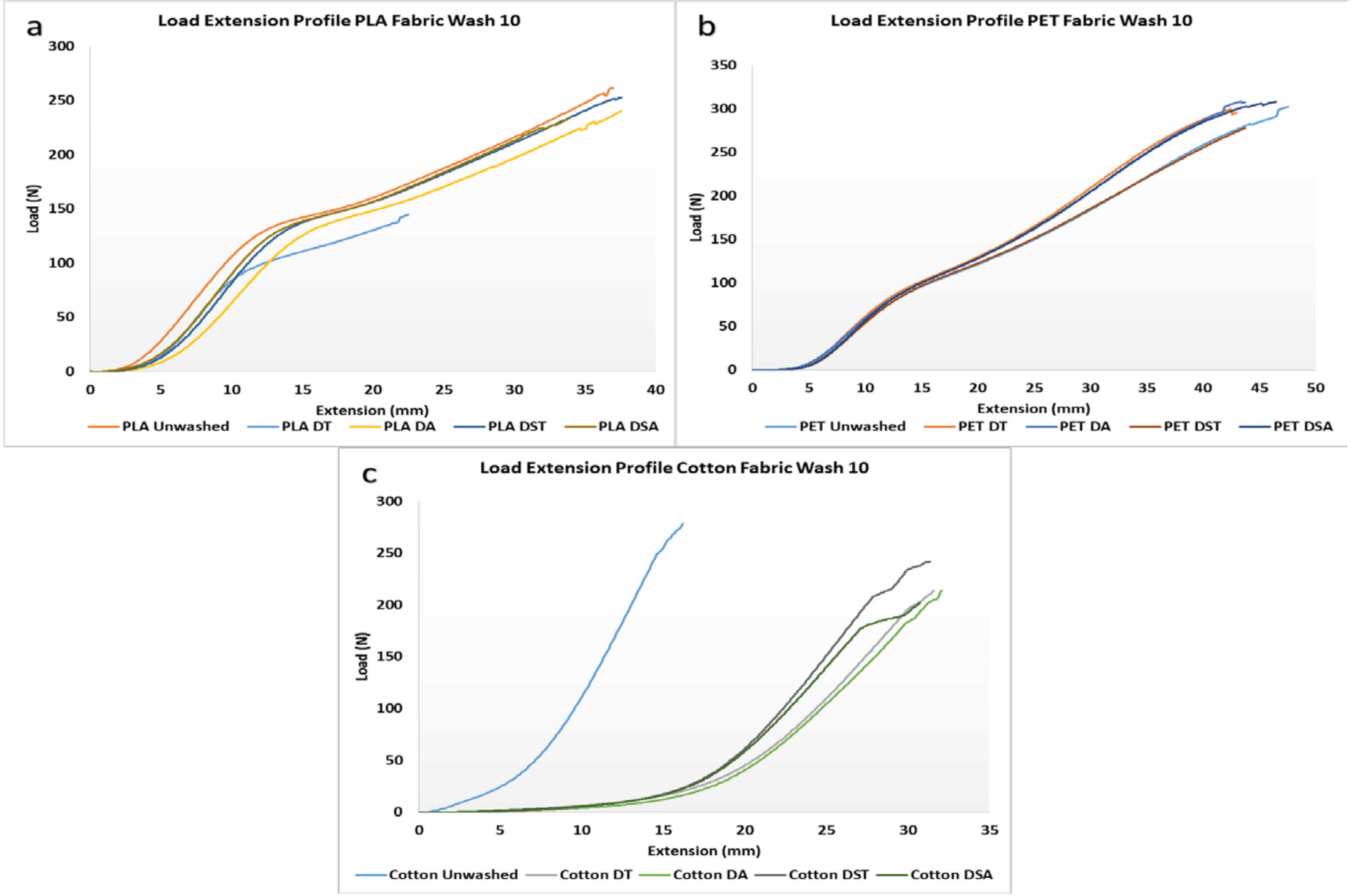

Figure 4.13: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 10 laundry cycles

Although the load-extension curve for PET fabric (Figure 4.13b) showed slight difference around the viscoelastic region, the linear elastic region exhibited parallel slopes for all laundry treatments. In addition, when compared to the unwashed fabric, the yield load and the extension at yield were consistent after each laundry treatment. This suggests that despite 10 laundry cycles, the different laundry treatment is not likely to alter the linear elasticity of PET fabric. The result in Figure 4.13c suggests that as the laundry cycle increases, the load-extension curve for the cotton laundry treatments seems to be drawing close together. A closer examination of the curves shows a parallel linear elasticity for DT and DA, and for DSA and DST. In comparison to the unwashed fabric, the laundry treatments resulted in a further decline of 6.90%, 7.2%, 8.3% and 8.6% for DSA, DST, DA and DT respectively. However, the extension at the yield on the cotton fabric for all laundry treatments increased respectively by 6.2%.

4.4.5 Laundry Cycle 30

Figure 4.14a-c demonstrates the load-extension behaviour of PLA, PET and cotton fabrics after 30 laundry cycles. Like previous laundry cycles, the behaviour of PLA (Figure 4.14a) and PET (Figure 4.14b) fabrics before the linear elastic region have remained consistent. This suggests that, regardless of the laundry treatments, there appear to be no significant changes in the crystallinity of PLA and PET fabric even after 30 laundry cycles. Contrary to laundry cycles six and 10, the cotton fabric seems to exhibit different extensions before the linear elastic region. For DT and DSA, the extensions seem to be similar to laundry 10. However, DA showed a 3.58mm reduction, while DST increased by 3mm compared to laundry 10.

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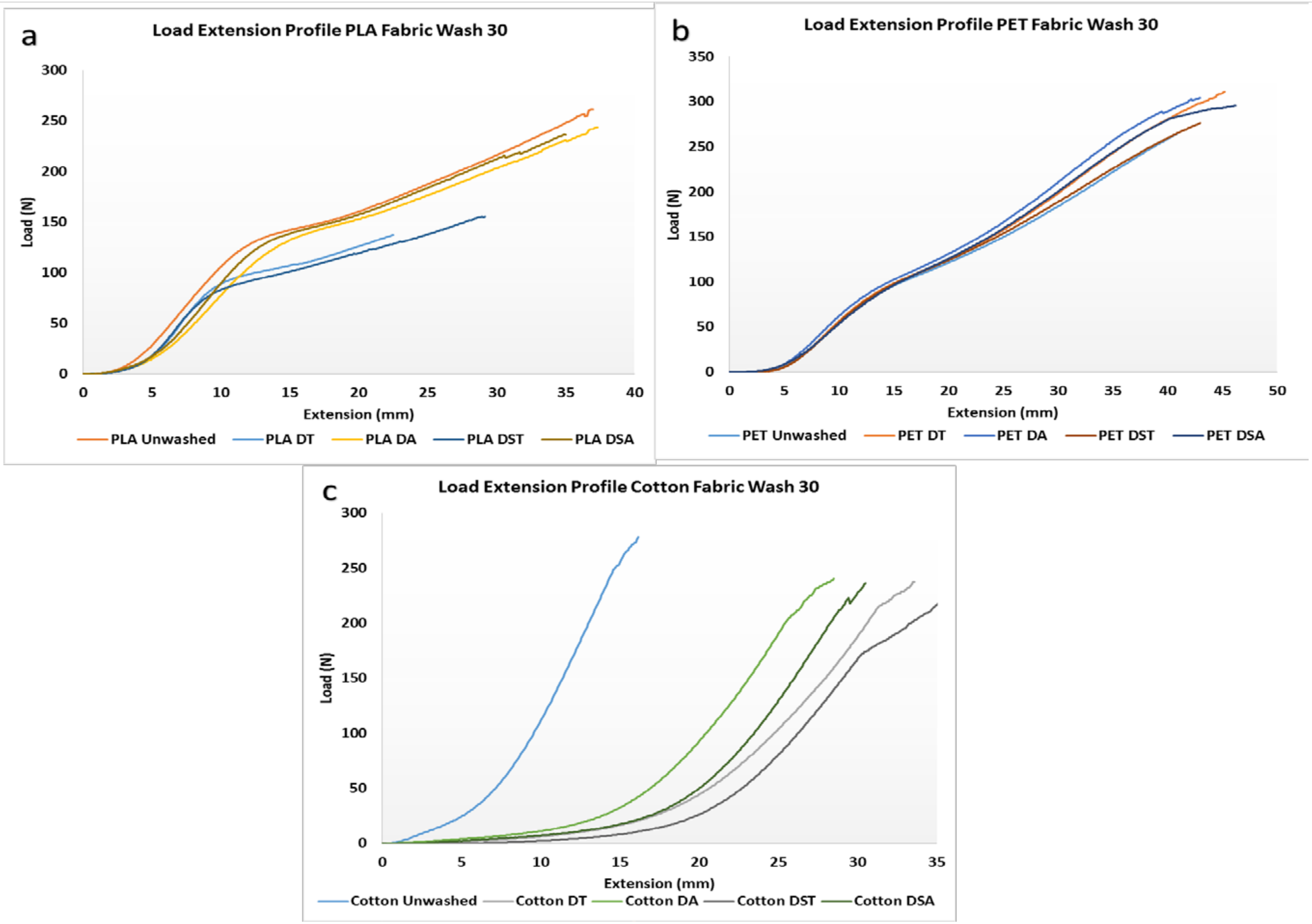

Figure 4.14: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 30 laundry cycles

Similar to laundry 10, Figure 4.14a suggests that the influence of the laundry treatments seems to be more significant in DT and DST. This is apparent by the unusual shape of the load-extension curve and the disparate slope around the linear elastic region for DT and DST. Moreover, the load-extension curve for DA and DSA show similar behaviour compared to the unwashed fabric.

For PLA fabrics, the influence of laundry treatments on the yield load (Figure 4.14a) resulted in a 5.5% and 4.6% decreases for DST and DT treatments respectively, while the fabrics washed in DA and DSA showed less than 1% decrease. In addition, when compared to the unwashed fabric, the influence of laundry treatments resulted in 2.1% and 2.6% decrease in extension for DT and DST, while DA and DSA showed a lower reduction of 1.9% and 0.8%. This suggests that the tumble-dried treatment produced a more significant effect on PLA fabric than the air-dried treatments.

The result in Figure 4.14b seems to confirm that, regardless of laundry regime and treatments, the behaviour of PET fabric shows a consistency in the shape of the load-extension curve, linear elasticity, yield load and extension at yield when compared to the unwashed fabric. For cotton fabric, Figure 4.14c shows that, in addition to the disparate shape of the load-extension curve and linear elasticity, the decrease in the yield load was found to be greater in DST (5.5%), followed by DA (3.4%) and 2.8% for DSA and DT. However, the tumble-dried treatment (DT and DST) produced a greater extension (between 8.6%-9.2%) than the air-dried treatments (6%-7.7%).

4.4.6 Laundry Cycle 50

Figures 4.15a-c demonstrates the load-extension behaviour of PLA, PET and cotton fabrics after 50 laundry cycles. The result shows that the extension of the linear elastic region for all laundry treatments, increased to ~5 mm for PLA (Figure 4.15a) similar to PET fabrics (Figure 4.15b) which have remained consistent throughout the laundry regime. For cotton, Figure 4.15c shows a significant (22.75 mm) extension for DST followed by 19.92 mm, 18.42 mm and 17.42 mm for DT, DA and DSA treatments respectively.

Figure 4.15a shows an influence of the laundry treatments on PLA fabric as evident by the shape of the load-extension curve and the linear elastic region for compared to the unwashed fabric. However, when compared to the unwashed fabric, DT resulted in a 4.9% decrease in yield load, but with a lesser extensionwhereas DA, DSA and DST resulted in a less than 1% decrease in yield load with greater extension of 2%, 2% and 5% respectively. This suggests that, for PLA, tumble-drying treatment seems to have an effect on the elasticity and extension within the elastic limit of the fabric.

Although the load-extension curve for PET fabric (Figure 4.15b) showed a slight difference in the viscoelastic region, the linear elastic region exhibited parallel slopes for all laundry treatments. This is also evident in the consistent yield load and extension at yield when compared to the unwashed PET fabric after each laundry treatment. This suggests that, despite 50 laundry cycles, different laundry procedures are not likely to alter the linear elasticity of PET material.

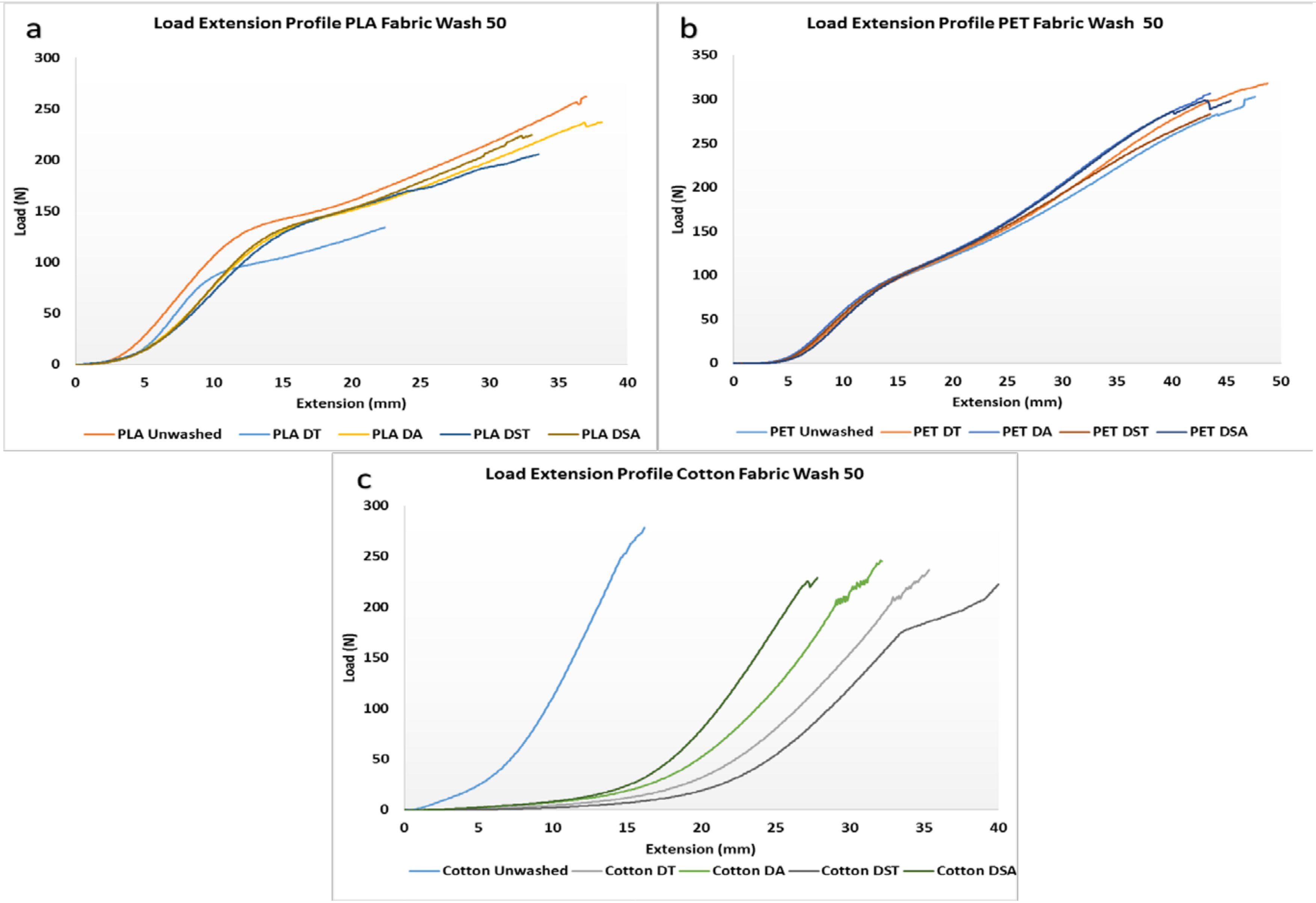

Figure 4.15: Influence of different laundry treatments on: (a) PLA, (b) PET and (c) Cotton fabrics after 50 laundry cycles

The result in 5.15c shows that, in addition to the disparate shape of the load-extension curve and linear elasticity, the influence of laundry treatments on cotton led to a 5.1% decrease in the yield load for DST, followed by 3.1% for both DT and DA, and 2% for DSA. Similar to laundry 30, the tumble-dried treatment (DT and DST) produced greater extension of 10.2% and 12.9% respectively, than the air-dried treatments (DSA and DA) which produced 6.7% and 7.9% increase in extensions.

4.5 Investigation of the influence of laundry treatments on the tensile properties of PLA, PET, and cotton fabric after 50 laundry cycles

In this section, the effect of laundry regime and different laundry procedures on the tensile properties of PLA, PET and cotton fabric is investigated. Analysis of variance is also performed to validate any influence for laundry regime and the laundry treatments on tensile modulus, tensile strength, percentage extension and load at break for each fabric type.

4.5.1 Tensile Modulus

4.5.1.1 Polylactic acid fabric

Tensile modulus depicts the stiffness and the tendency of the material to deform elastically when the load is applied. The higher the tensile modulus, the stronger and more resistant the fabrics are to laundry regime and the treatments. Figure 4.16 shows the effect of different laundry treatments on the tensile modulus of PLA during a regime of 50 laundry cycles. A summary of statistics and standard deviation of tensile modulus for PLA, PET and cotton by laundry treatment and number of laundry cycles is given in Appendix 1.

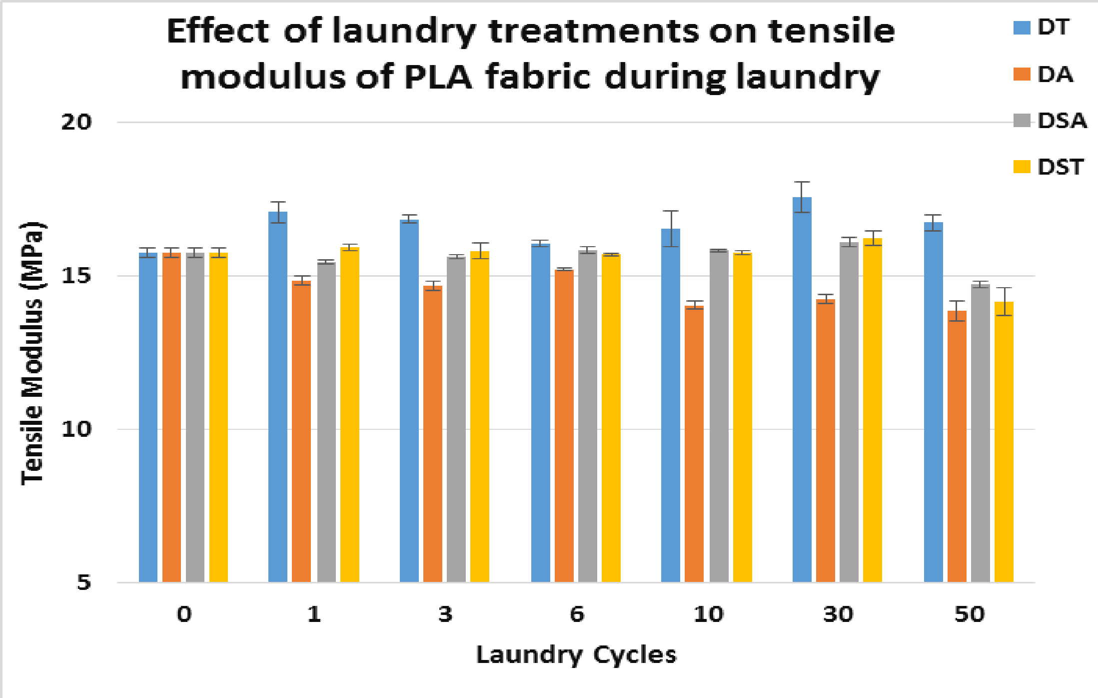

Figure 4.16: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on tensile modulus of PLA fabric. Error bars: 95% CI, n=5

The DT treatments resulted in 6-10% increase in tensile modulus during 50 laundry cycles. However, DA treatment resulted in a steady decline of 2-6% in tensile modulus with increasing laundry cycles, while no significant change was observed in tensile modulus of PLA with laundry treatments DSA and DST. The effect of DT treatment on PLA fabric resulted in 5-8% increase in tensile modulus between 1 and 6 laundry cycles, 10% after 30 laundry cycles and then reduced to 6% after 50 laundry cycles. The result of DA treatment on PLA fabric resulted in 4-6% increase in tensile modulus between 1 and 6 laundry cycles and 10-12% between 10 and 50 laundry cycles.

The result of DSA treatment on the fabrics showed no difference in tensile modulus of PLA between the unwashed fabric up to 30 laundry cycles after which it decreased by 7% after 50 laundry cycles. The result of DST laundry treatment show that there is no difference in the tensile modulus of PLA fabric (Figure 4.16) up to 30 laundry cycles, however, the tensile modulus reduced by 10% after 50 laundry cycles. This suggests that washing PLA in detergent plus fabric softener and tumble-drying up to 30 cycles retains the tensile modulus of the material. Analysis of variance showed that the effect of the laundry treatment on the tensile modulus of PLA was significant ($p<0.001$) for DT, DA, DSA and DST (see Appendix 2). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of the laundry treatment on PLA fabric. The impact of the interaction of laundry regime and laundry procedures (Appendix 2) on the tensile modulus of PLA fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments the tensile modulus of PLA fabric.

4.5.1.2 Polyethylene terephthalate fabric (PET)

Figure 4.17 shows that the effect of different laundry treatments on the tensile modulus of PET fabric resulted in 10.98 MPa, 11.26 MPa, 11.84 MPa and 11.36 MPa increase in the tensile modulus for DT, DA, DSA and DST respectively compared to the unwashed fabric (10.70 MPa) after 50 laundry cycles. This increase is further enhanced with the use of fabric softener.

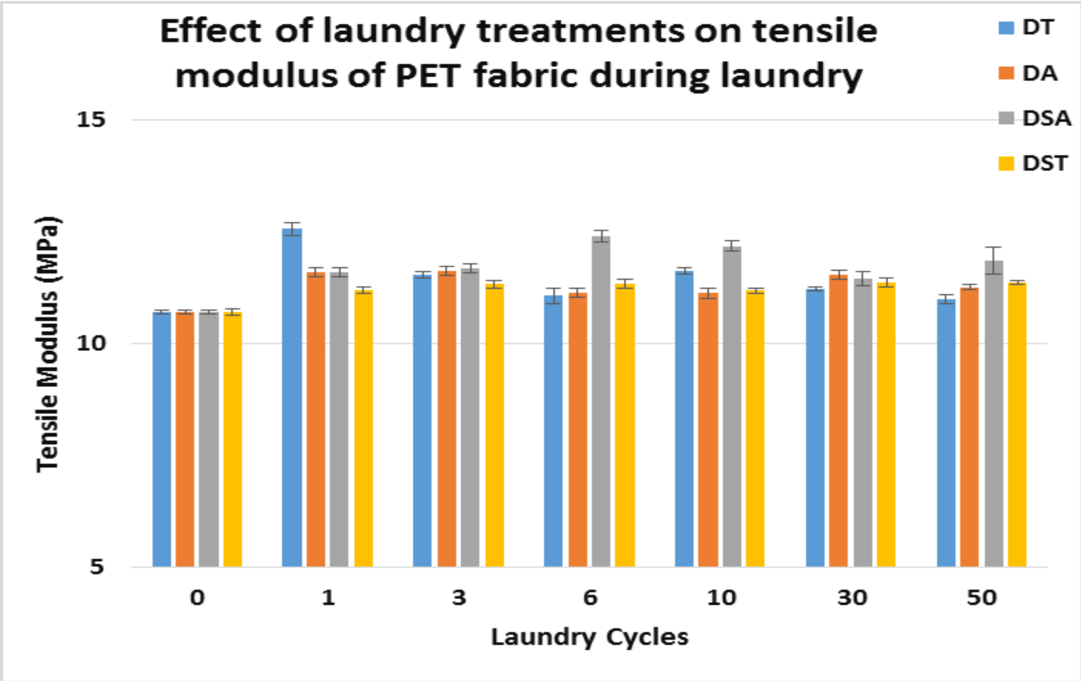

Figure 4.17: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-Tumble dry (DST) and detergent-softener-air dry (DSA) on tensile modulus of PET fabric. Error bars: 95% CI, n=5

The effect of DT treatment on the tensile modulus of PET fabric showed a 17% increase after the first laundry cycle, after which it reduced and fluctuated between 3-9% with increasing laundry cycles. The reason for the initial high increase could be an increase in the tightening and friction between the yarns due to the cylindrical shape of the fibres. However, as the laundry cycles increase, PET fabric seems to relax considerably, which might account for the reduction in the effect of DA treatment on PET fabric.

The effect of DSA treatment led to a greater increase (8-9%) in tensile modulus between laundry cycles one and three and then reduced to 4-5% between 10-50 laundry cycles. The effect of DST laundry treatment on PET fabric showed a steady increased tensile modulus and remained stable between 4-6% as the laundry cycle increased. In DSA treatment, the tensile modulus of PET fabric increased gradually by 8-16% between one and 10 laundry cycles, after which it decreased to 11% after 50 cycles. Analysis of variance showed that the effect of the number of laundry cycles and laundry treatment on the tensile modulus of PET after 50 laundry cycles was significant (p<0.05) for DT, DA, DSA and DST (Appendix 1). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of the laundry treatment on PET fabric. The impact of the interaction of laundry regime and laundry procedures (Appendix 2) on the tensile modulus of PET fabric was statistically significant (p<0.001), supporting the alternative hypothesis Ha_2: there is an interaction between the laundry regime and the laundry treatments the tensile modulus of PET fabric.

4.5.1.3 Cotton Fabric

The influence of different laundry treatment on the tensile modulus of cotton fabric (Figure 4.18) resulted in 16.42 MPa, 17.44 MPa, 21.24 MPa and 15.54 MPa decrease in tensile modulus for DT, DA, DSA and DST respectively compared to the unwashed fabric (29.34 MPa) after 50 laundry cycles.

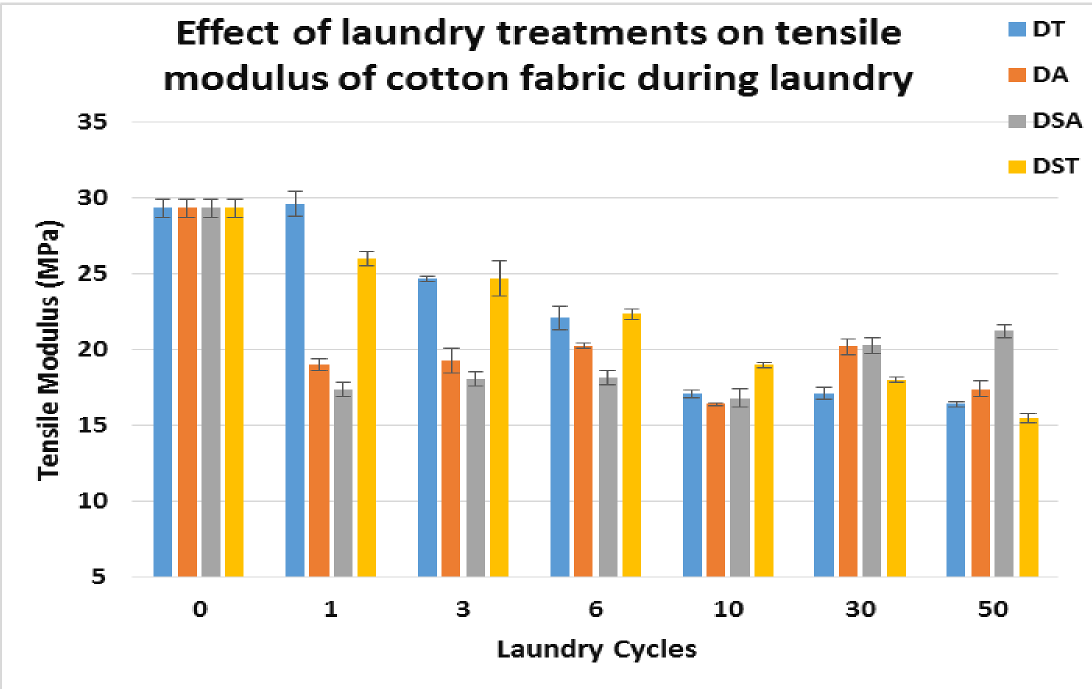

Figure 4.18: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on tensile modulus of cotton fabric. Error bars: 95% CI, n=5

The effect of DT treatment on cotton fabric showed no difference in the tensile modulus of the unwashed cotton fabric and laundry cycle one. However, as the laundry cycle increased the tensile modulus declined steadily until laundry cycle 10 after which it remained consistent up to laundry cycle 50. DA treatment resulted in a 31-44% decrease in tensile modulus with increasing laundry cycles. In DST treatment, there was a decrease of 11%, 16%, 24%, 35%, 39%, and 47% in tensile modulus with increasing laundry cycles. DSA treatment resulted in a 38-43% decrease in tensile modulus between laundry cycles one and 10, but after 30 and 50 laundry cycles, it decreased by 28-31%.

Analysis of variance showed that the effect of the number of laundry cycles and laundry treatments on the tensile modulus of cotton after 50 laundry cycles was significant ($p<0.05$) for DT, DA, DSA and DST (Appendix 1). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of the laundry treatment on cotton fabric. The impact of the interaction of laundry regime and laundry procedures (Appendix 2) on the tensile modulus of cotton fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments the tensile modulus of cotton fabric.

4.5.2 Tensile Strength

A summary of statistics and standard deviation of tensile strength for PLA, PET and cotton by laundry treatment and number of laundry cycles is given in Appendix 3

4.5.2.1 Polylactic acid fabric

Figure 4.19 shows the effect of laundry treatments on the tensile strength of PLA fabric during 50 laundry cycles.

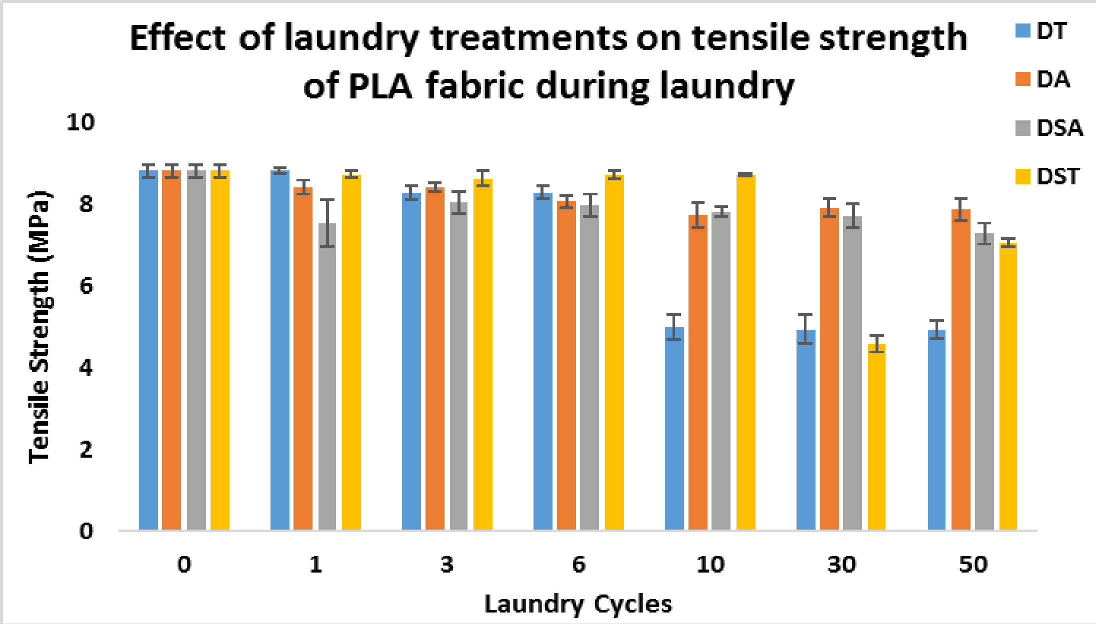

Figure 4.19: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on tensile strength of PLA fabric. Error bars: 95% CI, n=5

Analysis of the results shows that after 50 laundry cycles fabrics washed in DT treatments had the lowest tensile strength (4.94 MPa) followed by DST (7.06 MPa), DSA (7.29 MPa) and DA (7.88 MPa). PLA fabric in laundry treatment DT showed similar tensile strength (8.82 MPa) between the unwashed fabric and laundry cycle 1, and between laundry cycles 3 and 6 (8.3 MPa), after which it decreased to 4.9 MPa after 10-50 laundry cycles. Fabrics in DST treatment showed no significant changes in tensile strength (8.63-8.82 MPa) up to 10 laundry cycles but decreased sharply to 4.59 MPa after 30 laundry cycles. The reason for the sudden decrease after 30 laundry cycles could be machine error during the tensile measurement but, even if this was so, the result could be disregarded since the tensile strength increased again to 7.06 MPa after 50 laundry cycles. The effect of DST treatment was found to be significant ($p<0.001$), on PLA fabric across the range of laundry cycles. Fabric washed in DSA treatments resulted in a decrease in tensile strength from 8.82 MPa for the unwashed fabric to 7.54 MPa after laundry cycle one, after which it increased again to 8.04 MPa after laundry cycle three. There appeared to be a significant difference in the tensile strength of laundry cycles six and 50 (Figure 4.19).

Analysis of variance showed that the effect of the laundry treatments on the tensile strength of PLA fabric was significant ($p<0.001$) for DT, DSA, DA and DST after 50 laundry cycles (Appendix 4). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of all laundry treatments on the tensile strength of PLA. The impact of the interaction of laundry regime and laundry procedures (Appendix 4) on the tensile strength of PLA fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the tensile strength of PLA fabric.

4.5.2.2 Polyethylene terephthalate fabric (PET)

Figure 4.20 shows the effect of laundry treatments on the tensile strength of PET fabric during 50 laundry cycles.

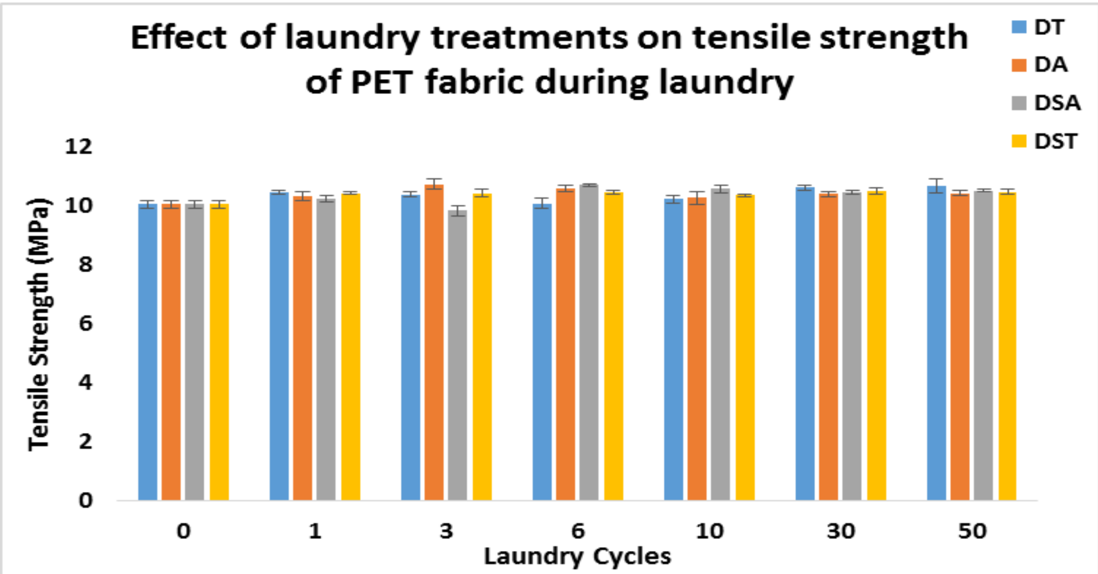

Figure 4.20: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on the tensile strength of PET fabric. Error bars: 95% CI, n=5

The effect of DT treatment resulted in similar tensile strength (10.0-10.5 MPa) between the unwashed fabric and laundry cycle 10 after which it increased slightly to 11 MPa after laundry cycle 30 and 50. The results of the DST treatments show that there was practically no difference in the tensile strength of PET fabric during the laundry regime. For fabrics washed in DSA treatment, the tensile strength was consistent with the first six laundry cycles and then increased slightly to 10.5-10.7 MPa during the next laundry cycles 10-50. For the fabric washed in DA treatment, the result shows that there was no difference in tensile strength (10.3 MPa) after laundry cycle one. This then increased slightly to 10.6 MPa after cycles six and 10; however, it reduced again to 10.3 MPa after cycles 30 and 50.

Analysis of variance showed that the effect of the laundry treatments on PET fabric was significant ($p \leq 0.05$) for DT, DSA and DST but not significant ($p=0.07$) for DA after 50 laundry cycles. This supports the alternative hypothesis of the research Ha_1: there is a significant effect of DT, DSA and DST laundry treatments on the tensile strength of PET, but rejects it for DA laundry treatment (Appendix 3). The impact of the interaction of laundry regime and laundry procedures (Appendix 4) on the tensile strength of PET fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the tensile strength of PET fabric.

4.5.2.3 Cotton fabric

Figure 4.21 shows the effect of laundry treatments on the tensile strength of cotton fabric during 50 laundry cycles.

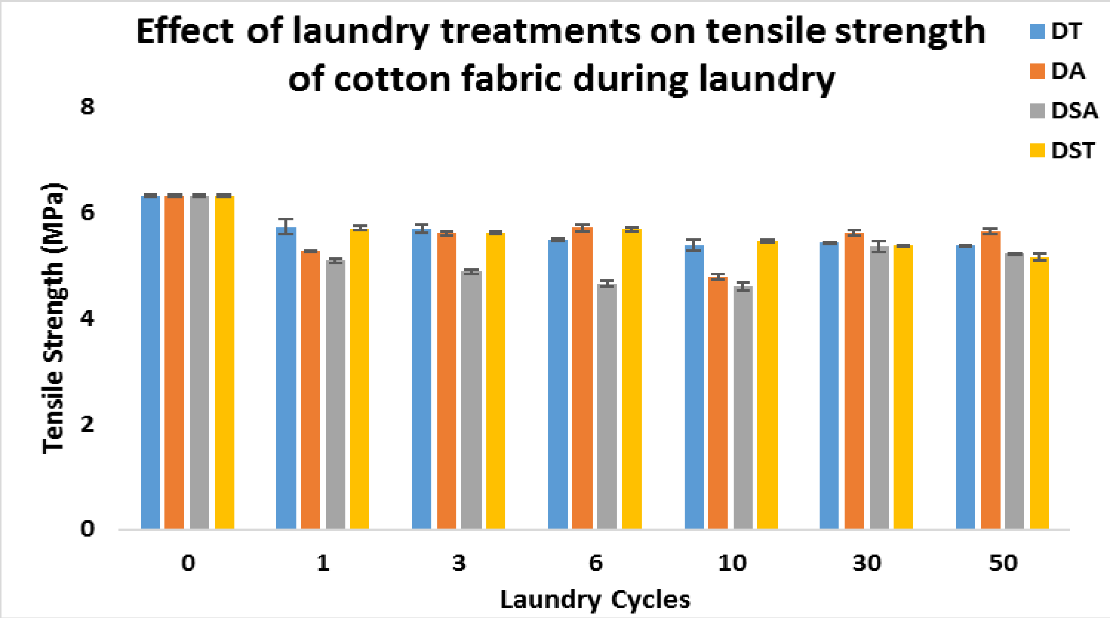

Figure 4.21: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on the tensile strength of the cotton fabric. Error bars: 95% CI, n=5

Analysis of the result shows that after 50 laundry cycles, there was a general decline in the tensile strength of cotton fabric because of different laundry treatments. Laundry treatment DT resulted in a gradual decrease in tensile strength from 6.3 MPa for unwashed fabric to 5.4 MPa after cycle 10 and then becomes consistent (5.4 MPa) between cycles 30 to 50. A similar trend is observed for cotton fabric washed in DST treatment. For fabrics washed in DSA laundry treatment, there was a significant decrease from 6.3 MPa for unwashed fabric to 5.0 MPa after laundry cycle one. With increasing laundry, the tensile strength decreased gradually to 4.6 MPa after 10 laundry cycles and then increased again to 5.4 MPa after cycles 30 and 50. In laundry treatment DA, there was a significant decrease in tensile strength from 6.3 MPa for unwashed fabric to 5.6 MPA after 50 laundry cycles.

Analysis of variance showed that the effect of laundry regime and the laundry treatments on cotton fabric were significant ($p \leq 0.05$) for DT, DA, DSA and DST after

50 laundry cycles (Appendix 3). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of all laundry treatments on the tensile strength of cotton. The impact of the interaction of laundry regime and laundry procedures (Appendix 4) on the tensile strength of cotton fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the tensile strength of the cotton fabric.

4.5.3 Load at Break

A summary of statistics and standard deviation of the load at break for PLA, PET and cotton by laundry treatment and number of laundry cycles is given in Appendix 5.

4.5.3.1 Polylactic acid fabric

Figure 4.22 shows the effect of laundry treatments on the load at break of PLA fabric during 50 laundry cycles.

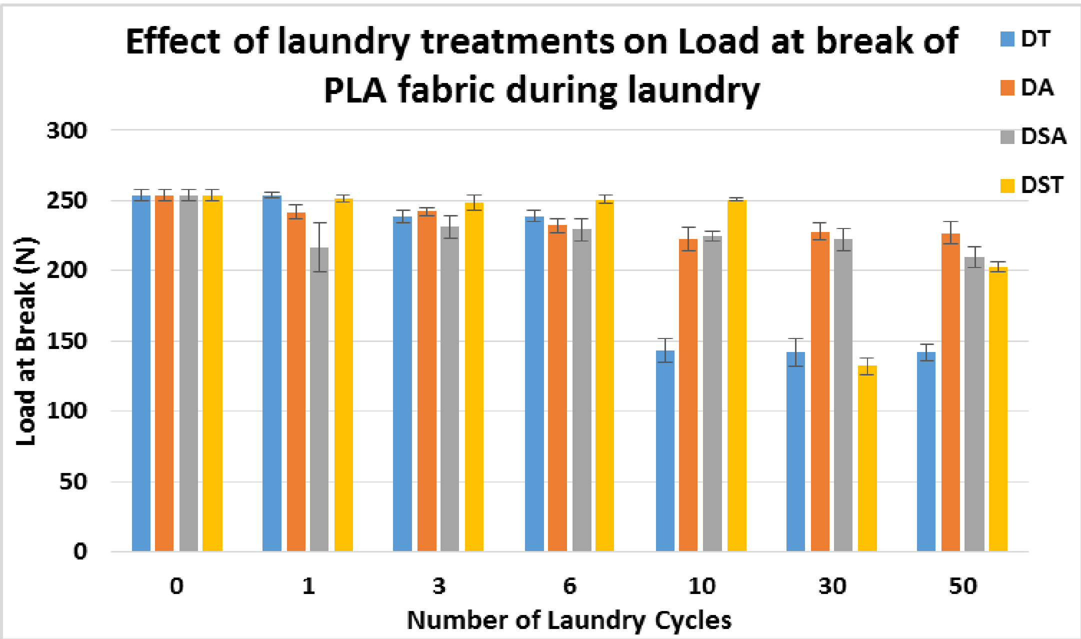

Figure 4.22: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on load at break of PLA fabric. Error bars: 95% CI, n=5

Analysis of the results shows that fabrics washed in DT treatments had the lowest load at break (142 N) followed by DST (203 N), DSA (210 N) and DA (226.68 N) after 50 laundry cycles. PLA fabric in laundry treatment DT showed similar load at break (254 N) between the unwashed fabric and laundry cycle one, and between laundry cycles three and six (238 N), after which it decreased to 142 N after 10-50 laundry cycles. Fabrics in DST treatment showed no significant changes in load at break (248-254 N) up to 10 cycles but decreased sharply to about 130-203 N after 30 and 50 laundry cycles. Fabric washed in DSA treatments resulted in a reduction in load at break from 254 N for unwashed fabric to 217 N after laundry cycle one, then increase again to 231 N after laundry cycle three. There appeared to be a significant difference in the load at break between laundry cycles six and 50.

Analysis of variance showed that the effect of the laundry treatments on the load at break of PLA fabric was significant ($p<0.05$) for DT, DSA, DA and DST after 50 laundry cycles (Appendix 6). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of all laundry treatments on the load at break of PLA. The effect of the interaction of laundry regime and laundry procedures (Appendix 6) on the load at break of PLA fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the load at break of PLA fabric.

4.5.3.2 Polyethylene terephthalate fabric (PET)

Figure 4.23 shows the effect of laundry treatments on the load at break of PET fabric during 50 laundry cycles.

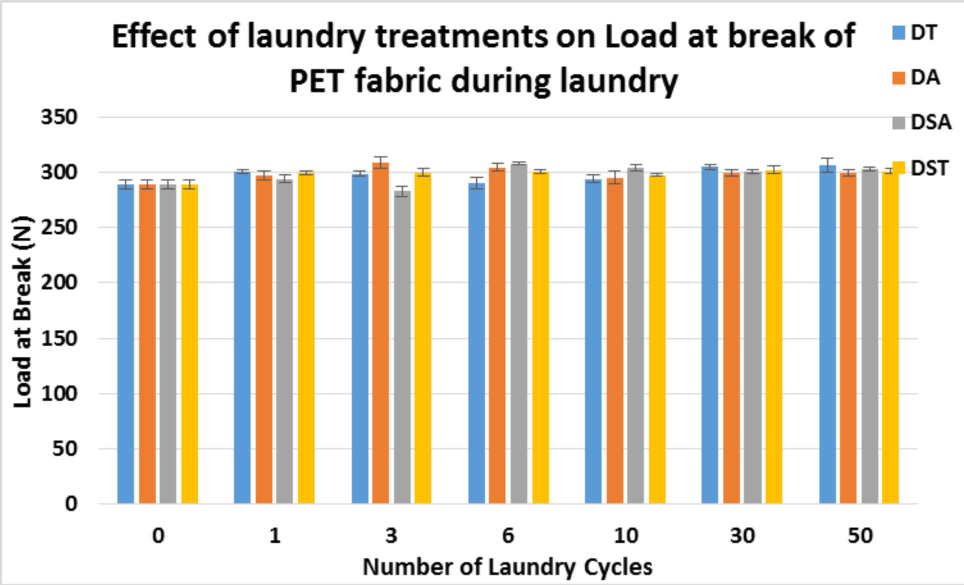

Figure 4.23: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on load at break of PET fabric. Error bars: 95% CI, n=5

Analysis indicated that DT treatment resulted in similar load at break (289-294 N) between the unwashed fabric and laundry cycle 10 after which it increased slightly to 306N after cycles 30 and 50. The results of the DST treatments show that the difference in the load at break of PET fabric during the laundry regime was not significant. For fabrics washed in DSA treatment, the load at break was consistent with the first six laundry cycles and then increased slightly between 300-303 N during the next laundry cycles 10-50. For the fabric washed in DA treatment, the results show that there was no difference in load at break after laundry cycle one compared to the unwashed fabric. This then increased slightly to 304-308 N after 3 and 6 cycles; however, as laundry cycle increased it reduced again between 295-299 N after cycles 10, 30 and 50.

Analysis of variance showed that the effect of the laundry treatments on the load at break of PET fabric was significant ($p \leq 0.05$) for DT, DSA and DST but not significant ($p=0.07$) for DA after 50 laundry cycles (Appendix 5). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of DT, DSA and DST laundry treatments on the load at break of PET, but rejects it for DA laundry treatment (Appendix 5). The impact of the interaction of laundry regime and laundry treatments (Appendix 6) on the load at break of PET fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments for the tensile strength of PET fabric.

4.5.3.3 Cotton fabric

Figure 4.24 shows the effect of laundry treatments on the load at break of cotton fabric during 50 laundry cycles.

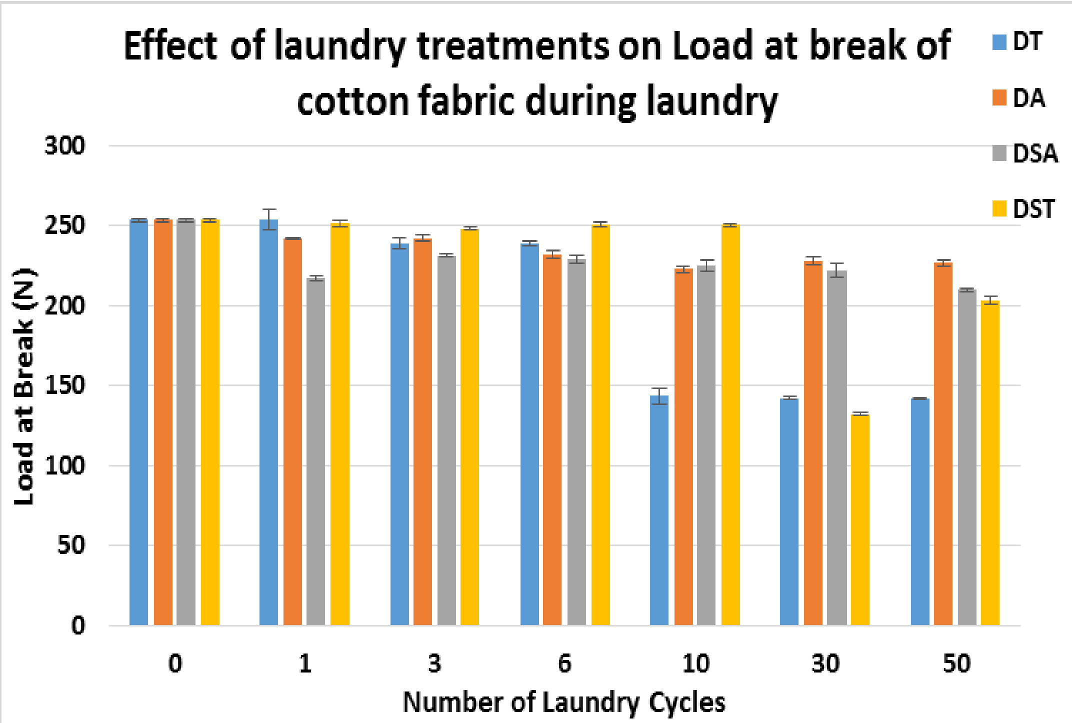

Figure 4.24: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-Tumble dry (DST) and detergent-softener-air dry (DSA) on load at break of cotton fabric. Error bars: 95% CI, n=5

Analysis of the results show that, after 50 laundry cycles, there was a general decline in the load at break of cotton fabric because of different laundry treatments. Laundry treatment DT resulted in a gradual decrease in load at break between 240-250 N from cycle 1-10 compared to 277 N for unwashed fabric after which it remained constant at

236 N between cycles 10 and 50. A similar trend is observed during the laundry cycles for cotton fabric washed in DST treatment. For fabrics washed in laundry treatments DSA, there was a significant decrease in the load at break from laundry cycle one to 10 compared to unwashed fabric. As the laundry cycle increased, the load at break increased again to 229 N after 50 cycles. In laundry treatment DA, the load at break decreased significantly to 247 N after 50 laundry cycles compared to the unwashed fabric.

Analysis of variance showed that the effect of laundry regime and the laundry treatments on the load at break for cotton fabric was significant ($p \leq 0.05$) for DT, DA, DSA and DST after 50 laundry cycles (Appendix 5). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of all laundry treatments on the load at break of cotton. The effect of the interaction of laundry regime and laundry procedures (Appendix 6) on the load at break of cotton fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the load at break of cotton fabric.

4.5.4 Percentage Extension

A summary of statistics and standard deviation of percentage extension at break for PLA, PET and cotton by laundry treatment and number of laundry cycles is given in Appendix 7.

4.5.4.1 Polylactic acid fabric

Figures 4.25 illustrate the effect of different laundry treatments on the change in length of the PLA, fabrics under a constant rate of extension during a regime of 50 laundry cycles. In general, the results of the unwashed fabrics showed that PET had the highest tensile extension followed by PLA and cotton.

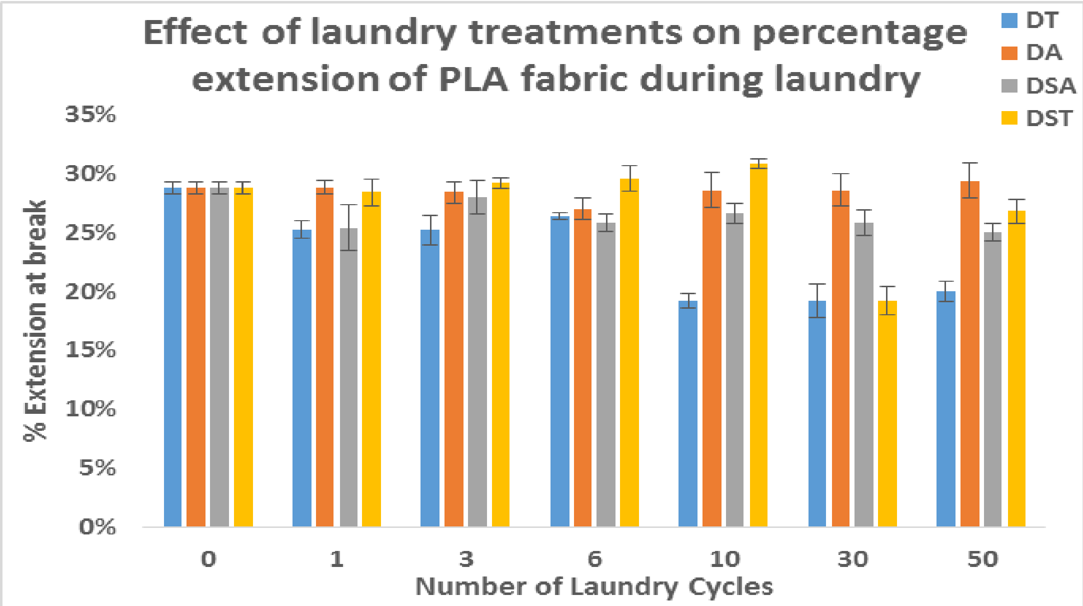

Figure 4.25: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on percentage extension of PLA fabric. Error bars: 95% CI, n=5

The effect of different laundry treatments on PLA (Figure 4.25) show that after 50 laundry cycles the DT treatment resulted in a decrease in percentage extension to 20%, followed by DSA (25%), while DA and DST showed no significant change in the extension of PLA compared to the unwashed fabric (29%). Further analysis of the effect of laundry treatments revealed that with increasing laundry cycles and laundry treatment DT, percentage extension decreased by 4-5% between cycles one and six, and then further declined by 9-10% between cycles 10 and 50 for PLA fabric. For laundry treatment DST, the percentage extension of PLA fabric remains almost the same throughout the laundry regime. The result of the effect of laundry treatments DA and DSA showed similar percentage extension for PLA compared to the unwashed fabric with increasing laundry cycles.

Analysis of variance showed that the effect of laundry treatment on the percentage extension of PLA fabric with increasing laundry regime was significant ($p<0.05$) for DT and DSA but not significant ($p=0.84$ and 0.20) for DA and DST treatments (Appendix 7). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of laundry treatments DT and DSA but rejects it for DA and DST on the percentage extension of PLA fabric. The effect of the interaction of laundry regime and laundry procedures (Appendix 8) on the percentage extension of PLA fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the percentage extension of PLA fabric.

4.5.4.2 Polyethylene terephthalate fabric (PET)

Figure 4.26 shows the effect of different laundry treatments on the percentage extension of the PET fabrics under a constant rate of extension during a regime of 50 laundry cycles.

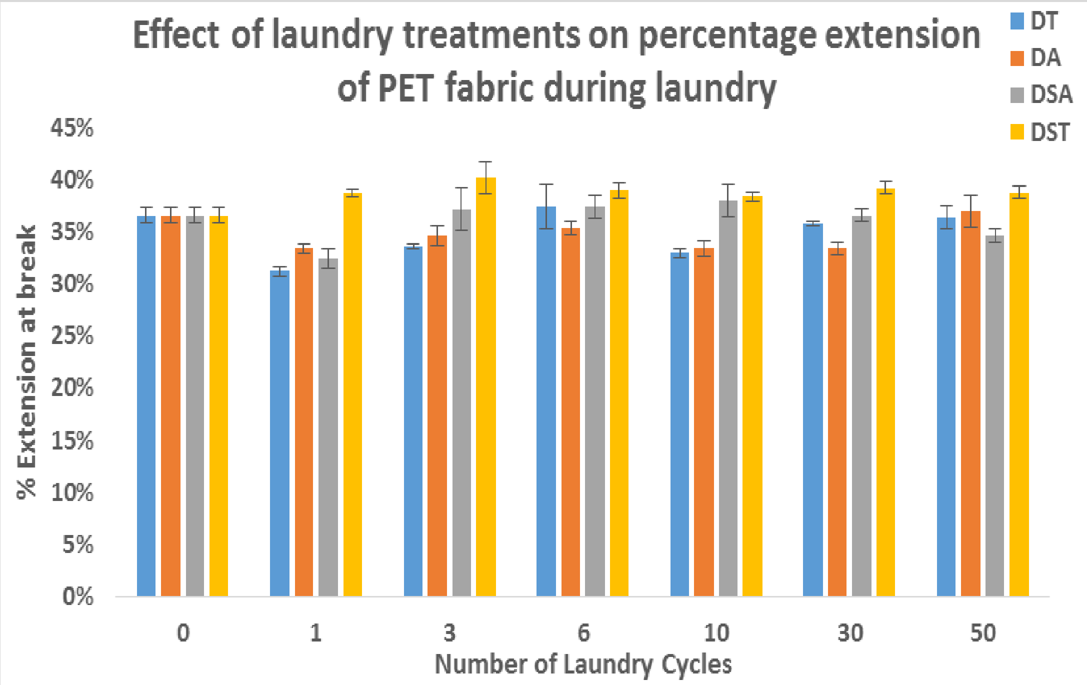

Figure 4.26: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on percentage extension of PET fabric. Error bars: 95% CI, n=5

For PET fabric, different laundry treatments did not result in any significant change in the tensile extension after 50 laundry cycles. However, further analysis showed that as the laundry regime increased, PET fabric showed 3-6% decrease in percentage extension between laundry cycles one and three in DT laundry treatment, which then increased and remained steady between laundry cycle six and 50. The result shows that no changes occurred between six and 50 laundry cycles compared to the unwashed PET fabric with increasing laundry cycles. The effect of laundry treatments DA and DSA showed similar tensile extension for PET compared to the unwashed fabric. With increasing laundry cycles and laundry treatment DST, the percentage extension of PET fabric remains almost the same throughout the laundry regime.

Analysis of variance showed that the effect of laundry treatment on the percentage extension of PET fabric with increasing laundry regime was significant (p<0.05) for

DT, DA and DSA but not significant (*p*=0.11) for DST treatments (Appendix 8). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of laundry treatments DT, DA and DSA but rejects it for DA and DST on the percentage extension of PET fabric. The effect of the interaction of laundry regime and laundry treatments (Appendix 8) on the percentage extension of PET fabric was statistically significant ($p<0.001$), supporting the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the tensile strength of PET fabric.

4.5.4.3 Cotton fabric

Figure 4.27 shows the effect of different laundry treatments on the percentage extension of cotton fabrics at a constant rate of extension during a regime of 50 laundry cycles.

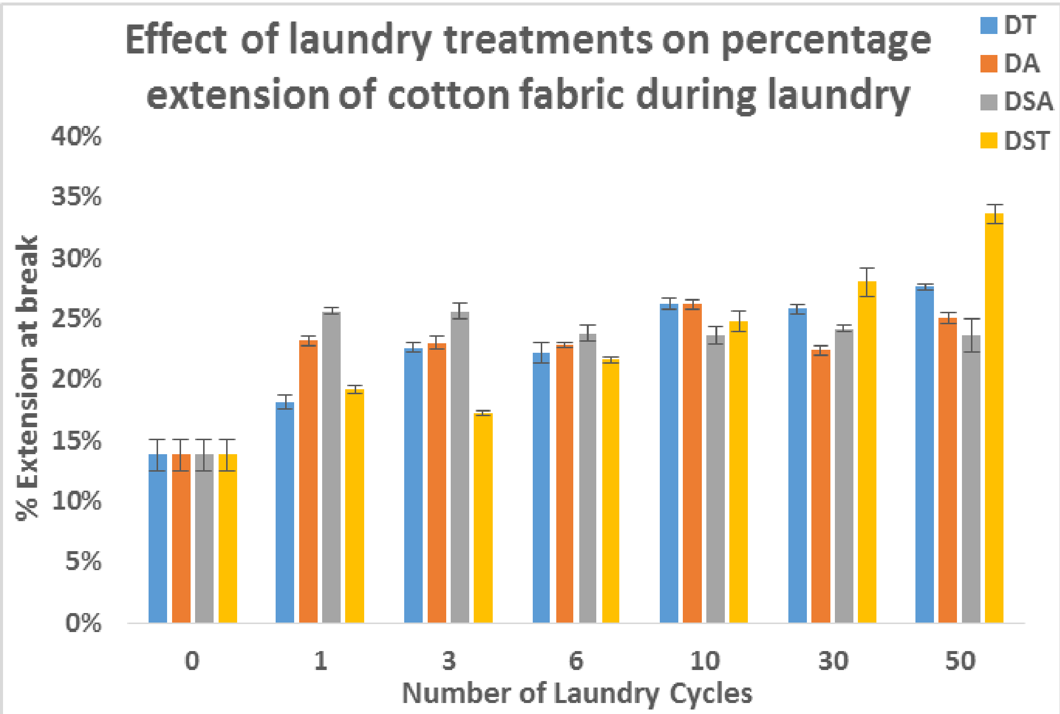

Figure 4.27: Effect of detergent-tumble dry (DT), detergent-air dry (DA), detergent-softener-tumble dry (DST) and detergent-softener-air dry (DSA) on percentage extension of cotton fabric. Error bars: 95% CI, n=5

The result showed an increasing effect of different laundry treatments on cotton fabric after 50 laundry cycles. Laundry treatment led to an increase in tensile extension to 34%, 28%, 25% and 24% for DST, DT, DA and DSA respectively. Further analysis showed that the percentage extensions for cotton fabric in DT treatment increased gradually by 4-9% between one and six cycles and then further increased by 12-14% between 10 and 50 cycles. During laundry treatment DST, as the laundry cycle increased, the percentage extension for cotton fabric increased gradually by 5-8% between laundry cycles one and six and then further increased by 11-20% between 10-50 cycles. However, laundry treatments DA and DSA showed a similar effect on the tensile extension of cotton fabric with increasing laundry cycles.

Analysis of variance showed that the effect of laundry treatment on the percentage extension of cotton fabric with increasing laundry regime was significant ($p<0.05$) for DT, DA, DST and DSA procedures (Appendix 7). This supports the alternative hypothesis of the research Ha_1: there is a significant effect of laundry treatments on the percentage extension of cotton fabric. The impact of the interaction of laundry regime and laundry procedures (Appendix 8) on the percentage extension of cotton fabric was statistically significant ($p<0.001$), the alternative hypothesis of the research Ha_2: there is an interaction between the laundry regime and the laundry treatments on the percentage extension of PLA fabric.

5 LIFE CYCLE ASSESSMENT

5.1 Introduction

This section of the research presents the use of life cycle assessment and its techniques as a means of evaluating the potentials of adopting PLA as an alternative fabric to cotton and PET. Based on the various literature reviewed in Section 2.9 of Chapter 2, the only method employed is the life cycle assessment. Therefore, this section will concentrate on life cycle assessment (LCA), its methods, applications and limitations regarding the fabrics studied. LCA is an environmental management tool used to estimate and evaluate the environmental impact of a product, process, activity, resource consumption, energy and environmental contamination of materials throughout their life cycles (Roy *et al.* 2009). These impacts, sometimes referred to as the environmental footprint of a product or service, may be beneficial or adverse. It is a cradle to grave approach, involving the collection and evaluation of quantitative data on the inputs and outputs of materials, energy, and waste flows associated with a product from and to the natural environment over its entire lifetime (Rebitzer *et al.* 2004). This section will follow the steps employed in a typical LCA as listed below:

- Goal and Scope Definition
- Functional Unit
- System boundary
- Life cycle inventory
- Life cycle impacts assessment
- Interpretation and recommendation

The goal and scope of the research are defined first; outlining the purpose of the study, the expected products, system boundaries, functional units and the assumptions considered. Next is the life cycle inventory analysis that involves data collection and calculation to quantify the inputs and outputs to the overall product system in its life cycle. The process flowing from the cultivation of corn and cotton/extrusion of crude oil for the production of PET to the manufacturing of the fabrics are outlined in this section.

The next section is the life cycle impact assessment where the environmental implications of a product, activity or service are identified and evaluated. Typically, a life cycle impact assessment of a product is usually carried out on a cradle to grave basis. However, due to various applications of textile fabrics (such as bed sheets, carpets and rugs, and upholstery) as well as the system boundary of this study (use phase of a t-shirt), the impact assessment is limited to a more comparable 'cradle-to-usage' of 0.25kg t-shirt made from PLA, PET and cotton fabric as opposed to the conventional cradle to grave. This approach takes account of all inputs and outputs from the production all through the fabric manufacturing and the laundry use phase of fabric produced from PLA, PET and cotton. This addresses objective 2 (section 1.3) of the research; to evaluate and compare the environmental performance of PLA, PET and cotton fabric from cradle to usage.

The purpose is to assess the contribution of products and services to impact category such as; greenhouse gas emission (GHG), water resources usage and the potential energy demand (PED). This phase of the LCA consists of the following steps: classification, characterisation, normalisation and evaluation. Classification assigns the data obtained from the life cycle inventory into collective impact groups and then the impact potentials or the magnitude of potential impacts on each inventory flow are calculated based on the inventory result from its corresponding environmental impact (e.g. modelling the possible effects of carbon dioxide and methane on global warming) (Roy *et al.* 2009). According to the ISO standard, the next two steps, normalisation and evaluation (weighting), are both voluntary (ISO 2006). Normalisation presents the potential impacts in ways that can be compared to all impacts getting the same units and assigning a weighting factor with respect to the level of importance of environmental burden.

The final section is the result interpretation. This is the last phase of an LCA process; it is also an important aspect because it allows conclusions to be drawn from the outcome of the inventory and the impact assessments. It provides a systematic technique for identifying and quantifying, checking and evaluating the information derived from the outcome of the life cycle inventory and the life cycle impact assessment. Two objectives defined by ISO 14043:2006 state that:

1. The results should be analysed, and the conclusion reached, any limitation experienced explained, and recommendations provided based on the findings of the impact assessments. These results must be interpreted in a transparent manner without any bias
2. A readily understandable, complete and consistent presentation of the outcome of the LCA is provided in accordance with the goal and scope of the study.

The key steps to consider when interpreting the results of the LCA are to identify the significant issues based on the life cycle inventory and the life cycle impact assessment, and to evaluate which of the issues consider completeness, sensitivity and consistency, and to draw a conclusion and recommendation (Curran and SAIC 2006).

5.2 Life Cycle Assessment (LCA)

In the 1990s, The Society of Environmental Toxicology and Chemistry (SETAC) sponsored workshops and projects to develop and promote a framework for conducting life cycle inventory analysis and impact assessment (Rebitzer *et al.* 2004). As a result of efforts by other organisations such as the International Organisation for Standardisation (ISO), a consensus was reached on a framework and a well-defined inventory methodology in 1997, (ISO 1997, Roy *et al.* 2009, Suh and Huppes 2005)

The development of an international standard for life cycle assessment known as the ISO 14000 series (ISO 14040:1997, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000) helped to consolidate procedures and methods for LCA. In 2006, the process was revised resulting in the publication of two new standards, ISO 14040 and ISO 14044 (Figure 5.1) to replace the existing one (ISO 2006). Although the core part of the technical content remained, the revision removed the errors associated with the previous one and improved reliability.

Figure 5.1: LCA Framework (ISO 2006)

5.2.1 Research Life Cycle Methodology

The life cycle assessment model was created using GaBi 4 LCA analysis software developed by PE International. The assessment analyses the environmental impact from the cradle to grave. The "grave" being the wash cycles that represent the end of use for each fabric. Figure 5.2 and 5.3 shows typical life cycle stages of natural and synthetic textiles.

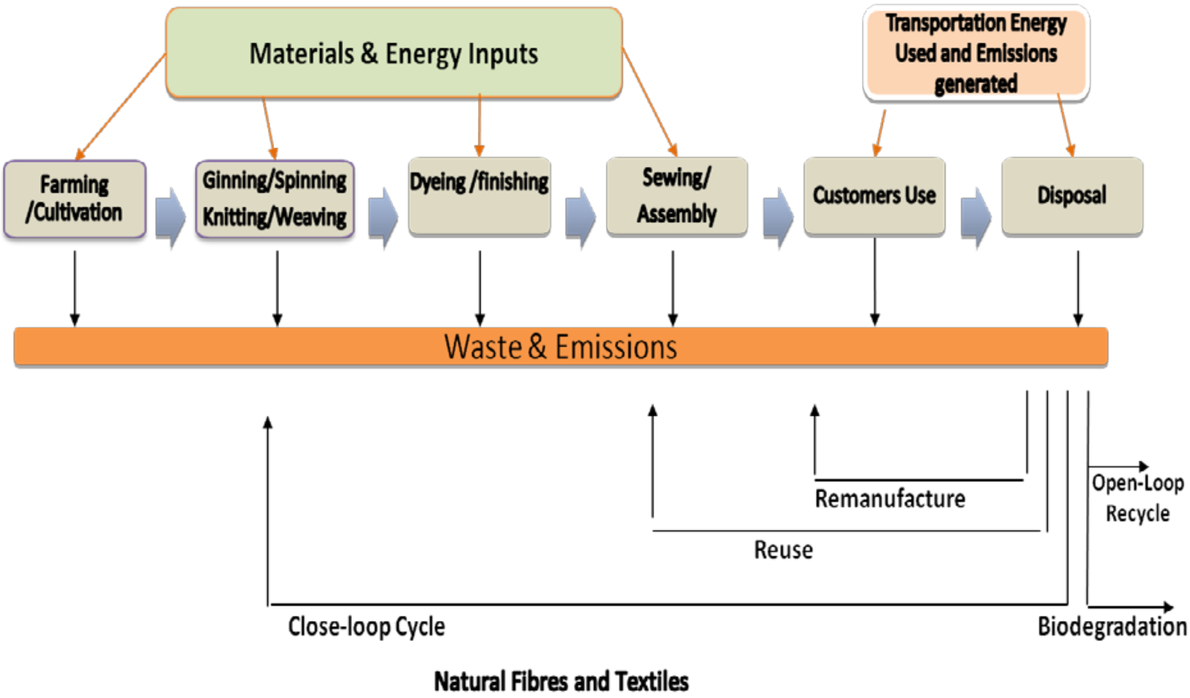

Figure 5.2: Life cycle Schematics for Natural Fibres and Textiles

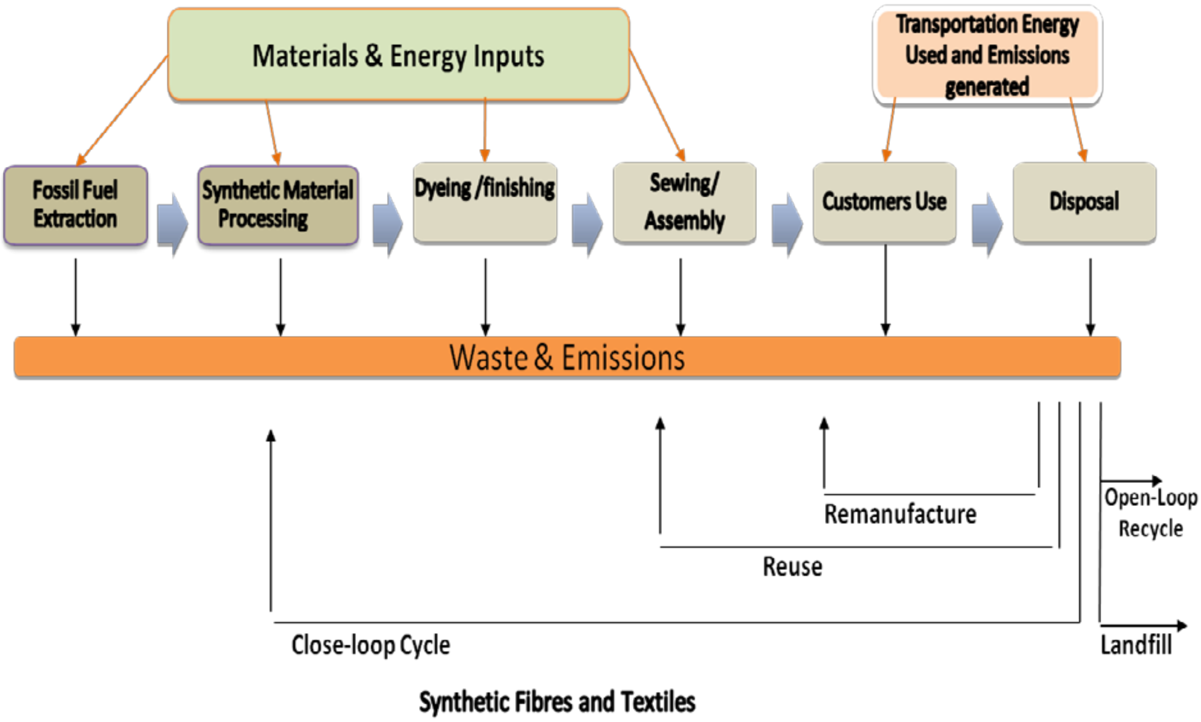

Figure 5.3: Life Cycle Schematics for Synthetic Fibres and Textiles

5.3 Goal Definition and Scoping

The goal and scope definition is the most important stage of a life cycle assessment because this phase determines the entire working plan. The purpose of the study is defined at this point, the expected product, the system boundaries, functional unit and the assumptions are determined before the study is carried out.

5.3.1 Research Goal and Scope

The goal of this aspect of the study is to assess the associated environmental impact during the use phase and the production of a 250g, a t-shirt made from PLA, PET and cotton fabric. With an emphasis on the use phase, where the input material at the fabric production stage was increased to manufacture a better quality t-shirt with longer lifetime: the environmental impact associated with this increase was also assessed. Impact categories such as the potential energy (fossil/nuclear) requirements, water demand and the Global Warming Potential (GWP 100 years) baseline. The GWP of a greenhouse gas (GHG), is the ratio of heat trapped by one unit mass of this GHG to that of one unit mass of CO_2 over a specified time interval (De_Richter and Caillol 2011). The GWP and an atmospheric lifetime of the three most important GHG are listed in Table 5.1.

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Source: (De_Richter and Caillol 2011)

The scope of this study is cradle-to-usage (Figure 5.5), modelled as three overall phases. This includes the ‘cradle to gate’ unit process of the production from the raw materials cultivation (corn and cotton) and extraction (crude oil) for PLA, cotton and PET fabric, the ‘gate to gate’ textile manufacturing and the ‘gate to laundry use’ of a 0.25kg t-shirt made from these fabrics.

5.4 Functional Unit

According to Carr (1995), there is a cumulative effect in the repeated washing process on the damaging of fabric such as shrinkage, distortion, fibre damage, stiffness, colour fading and cross staining by fugitive dyes occurs during laundry. These changes are highly dependent on the fibre type, fabric construction and finishing process, end-use applications as well as the laundry process. Therefore, these factors helped in defining the functional unit and system boundaries for the LCA carried out in this study. The system function expressed as a functional unit is determined by the environmental impact category and the aims of the investigation. The objective is to provide a reference unit that can be used to normalise the data derived from the inventory (Roy *et al.* 2009). For instance, the functional unit of the production of fibre can be defined as the amount of fibre produced from 1kg of cotton, hemp or any other fibre plant. Input and output flow diagram are often used to illustrate the system boundaries in LCA. A poor definition of the scope may lead to acquiring and analysing data that is beyond the context of the intended purpose of the study (Crawford 2008).

Two functional units are considered in this study**.** Firstly, in terms of the fabric end-use, the functional unit is defined as the production of a 0.25kg t-shirt or equivalent produced from polylactic acid, cotton and polyethylene terephthalate for; the inventory analysis, resource use and environmental performance. Secondly, since two fabrics can never be identical the quality and fabric specification not the same (Tobler-Rohr 2000), the functional unit is defined in terms of the number of washes per year. For example, using a typical school t-shirt that is washed throughout a school year.

5.4.1 Defining Functional Unit for a School t-shirt (t-shirt)

This aspect of the assessment intends at reflecting the functions performed by the materials. Therefore, it is necessary to work out the number of laundry cycles and a functional unit to assess and compare the life cycle impact of a typical school t-shirt made from PLA, PET or cotton material. The function is a typical school t-shirt, used for the whole year in the UK. The secondary aim is to improve the durability of the t-shirts (i.e., to enhance the fabric durability and increase the lifetime of PLA, PET and cotton from its experimental laundry life time(35, 42 and 43 wash cycles). According to De Saxce *et al.* (2012), the durability of a textile product requires the introduction of additional processes, raw materials or different types of fabric materials. Therefore, to improve the quality of PLA to last for extended laundry cycles, the quantity of material needed and any associated environmental impact a durability factor was calculated. The following calculation shows the number of laundry washings a school t-shirt is subjected to in a typical school year.

For one (1) t-shirt approximately	0.25 kg
Number of weeks (school year)	39-40 weeks
Approximate number of washes per week	2
Approximate numbers of wash per school year taking into account mid-term and other holidays	≈75 wash cycles

.

The functional unit was calculated to increase the laundry durability of the fabric to match the number of wash cycles for a school shirt (75), using the following equation:

$$FU_n = \frac{n}{n_{fabric}} * FU_{ni}$$

Equation 4

Where:

FU_n = Functional Unit required for n laundry cycles
n = Number of laundry cycles
n_{fabric} = Experimental lifetime laundry cycle of each fabric.
FU_{ni} = Initial functional unit (0.25kg)

The functional unit was incorporated into the LCA of each fabric to reflect the quantity of material needed to produce a t-shirt durable for 75 wash cycles and to compensate for the loss in tensile properties due to laundry regime. This is based on the assumption that the fewer the number of laundry cycles at which the fabrics shows signs of damage, the greater the environmental impact not just on the manufacturing process but also in the overall life cycle. In addition, the extended the durability of the fabric based on the laundry use phase, the lower the overall environmental impact. Figure 5.4 illustrates the life cycle matrix for enhancing the fabric by a durability factor to last up to n^{th} laundry-cycles, where n is 75 wash cycles per year for a school t-shirt.

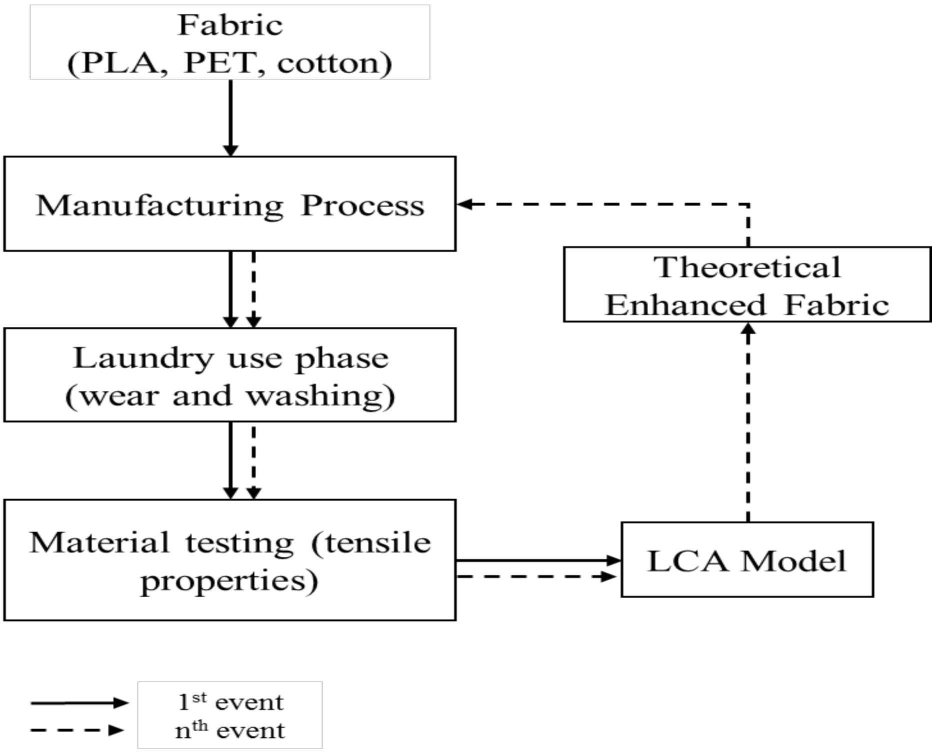

Figure 5.4: Schematic illustration of fabric lifecycle improvement

5.5 System Boundary

The conventional system boundary of a textile material life cycle assessment is from the cradle to grave and includes all the stages of crop cultivation to the use and disposal or possible recycling stages. The environmental consequence is usually categorised according to each phase of the life cycle i.e. the production phase, the use phase and the disposal phase. This takes account of all inputs and outputs from the production all through the fabric manufacturing and the laundry use phase of fabric produced from PLA, PET and cotton. However, as mentioned in Section 5.1 and discussed further in Section 5.3.1, due to applications of the fabric studied (as a t-shirt) within the use phase and the scope of the study, particular attention was given to the use phase where the experimental laundry regime was carried out to determine the change in mechanical properties and environmental impact associated with it. The laundry regime involves the number of washes (50 life cycle washes), the quantity of water and detergent used (45ml liquid detergent) and the machine load per wash cycle (5 kg). Within this boundary, an assessment of the laundry durability of each fabric was evaluated based on the measurement of the tensile properties. Figure 5.5 illustrate the schematic diagram of the system boundary showing the processes included in the life cycle environmental performance and comparison of PLA, PET and cotton t-shirt.

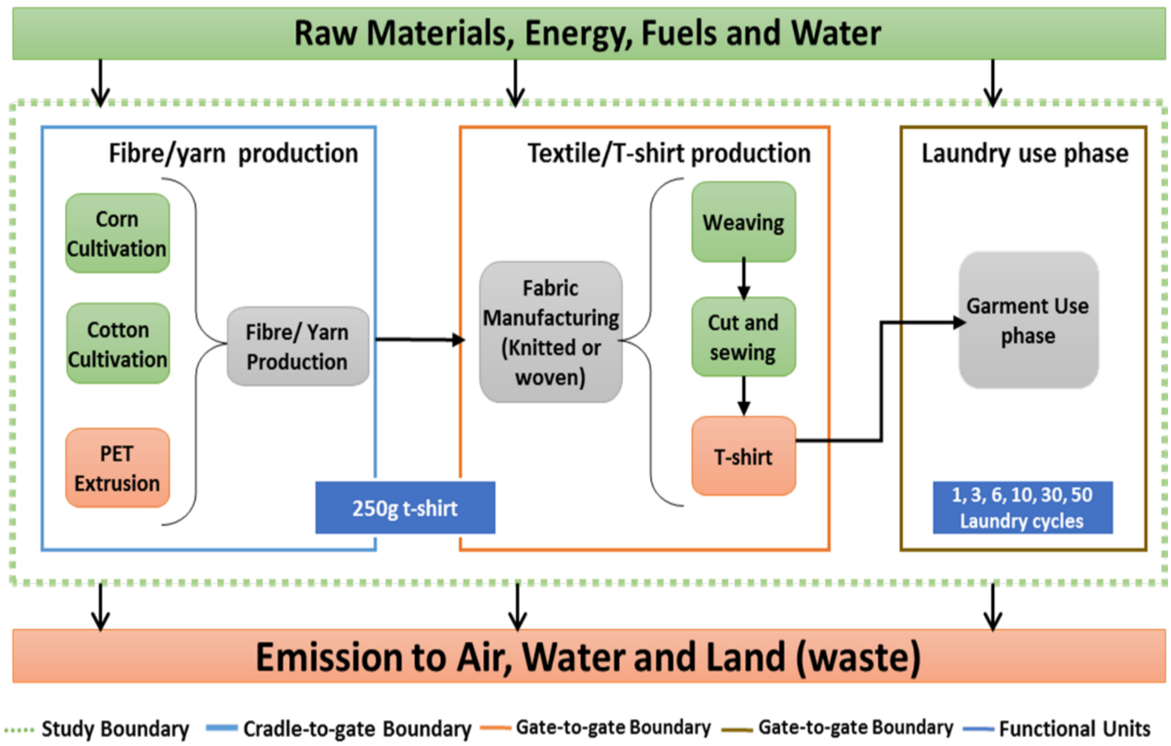

Figure 5.5: LCA System Boundaries and Functional Units

5.6 Assumption and Limitation of the Study

Various assumptions were made during this study. First, the equipment used (washing machine, tumble dryer and Instron tensile tester) and human errors were assumed to be random and had no significant influence on the results of the experiments. Secondly, since the laundry conditions simulate household laundering, all fabric types were washed together. This assumption also applied to the input and output inventory analysis of the laundry use phase. The study assumed that they would be similar to all three fabrics due to the mixed mode laundry method and, therefore, were excluded from the inventory.

Carrying out an LCA can be very demanding. A full-scale LCA takes a long time to complete and often the results are difficult to communicate. Many resources and much time are put into performing an LCA. Depending on the direction the LCA is inclined, gathering of data can be problematic, and the availability of data can significantly influence the accuracy of the result. Therefore, it is essential to evaluate the availability of data, the time required to conduct the study, and the financial resources for the long-term benefit of LCA. ISO 14040 focuses only on the environmental aspects of LCA, neglecting the social and economic aspects altogether.

From a textile point of view, Dahllöf (2004) identified constraints in the LCA methodology from different studies carried out on fibres and textiles. Gaps in data were an inherent problem, especially in the assessment of land use. This has led to high uncertainties in many LCA studies. Resource allocation has also been challenging. For instance in Kalliala and Nousiainen (1999b) allocation of the environmental burden was made to cotton fibre only. However, the unit process of producing cotton, produces both fibres and cottonseeds as a co-product. In this instance, the main environmental burden is applied to the cotton fibre (87%) due to the utility of cottonseeds (13%) for oil or as cattle feed, while the lint is used as raw materials for viscose fibres (Cartwright *et al.* 2011).

Lack of international consensus on the method of characterising land use has been a problem in LCA especially in the assessment of natural fibres. Occupancy and change in land use (transformation) are sometimes included as an impact category for land use, but the discrepancy in the classification of occupancy as resources or impact category is still argued. Change in land use is difficult to assess due to its relativity (Núñez *et al.* 2009).

5.7 Life Cycle Inventory Analysis

The life cycle inventory involves data collection and calculation to quantify the inputs and outputs to the overall product system in its life cycle. ISO 14040 defines this phase as the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (ISO 2006). This stage is the most work-intensive and time-consuming because it involves data collection from different sources as well as modelling of the product system, description and verification of data (Roy *et al.* 2009, Suh and Huppes 2002).

There are different methods available for life cycle inventory; however, the choice of methods often determines the significance of the results obtained. Therefore, the selection of the most relevant method for the life cycle assessment must be in relation to the goal and scope of the study as well as the resources and time available (Suh and Huppes 2005). According to Crawford, the accuracy and extent of the life cycle inventory analysis are dependent on the method choice (Crawford 2008). The four principal approaches to life cycle inventory are; process flows analysis, input-output analysis (I-O), hybrid analysis and matrix reorientation of a product system that uses a system of linear equations to solve inventory problems (Crawford 2008, Rebitzer *et al.* 2004).

Data from the various existing LCA databases together with LCA software can be used for processes that are not product-specific such as general data on the production of electricity. In the case of product-specific data such as the production of natural fibre from the agricultural process through fabric or composite manufacturing to its end, site-specific data are required. Such data should include all inputs and outputs from the process such as energy (renewable or non-renewable), water, raw materials, products and co-products, emissions (CO_2, CH_4, SO_2, NO_X and CO) to air and water (Roy *et al.* 2009).

5.7.1 Data Collection Process

As mentioned in Section 5.3.1, the scope of this study is cradle-to-usage, modelled as three overall phases; the 'cradle to gate' unit process of the production from the raw materials cultivation (corn and cotton) and extraction (crude oil) for PLA, cotton and PET fabric, the 'gate to gate' textile manufacturing and the 'gate to laundry use' of a 0.25kg t-shirt made from these fabrics.

Therefore, the primary data used in this study was obtained from the experimental laundry regime using the UK laundry consumer behaviour of washing different fabric types together on one cotton programme wash setting. The LCI data for the other unit process obtained from the GaBi 4 database and its integrated Ecoinvent v2.2 database (2007) represents a global average for crude oil production from Nigeria, China, and Europe for the manufacturing of PET fabrics, US and Switzerland (corn cultivation and harvesting). The assumption was that all fabrics were woven and sewn using the same process. Therefore, data for the production of t-shirt were adapted from the cotton weaving dataset from ecoinvent v2.2. Table 5.2 shows a summary of the inventory data and sources used in the LCA.

Table 5.2: Sources of inventory data used for LCA of PLA, PET and Cotton fabric

Data	*Data Source*	*Notes*
Crop production/feedstock (corn, cotton, PET) Pulp Production	Ecoinvent database (version 2.2) (Frischknecht 2003)	Site-specific
Fibre Production COT, PET, Maize/starch at farm	Ecoinvent database (version 2.2) (Frischknecht 2003)	Global specific
Power: Grid, Country specific	Ecoinvent database (version 2.2) (Frischknecht 2003) IEA energy statistics (IEA 2008)	Country specific. European electricity mix (used for NaOH and other chemical production): 55% from the UCTE grid, 13% from the NORTEL grid, 9% from the CENTRAL grid, 12% from the UK grid, and 1% from the Irish grid.
Heat: Grid, Country Specific	Ecoinvent database (Version 2.2) (Faist *et al.* 2003)	Grid heat from industrial gas boiler
Production of chemicals (e.g. caustic soda)	Ecoinvent database (Version 2.2) (Zah and Hischier 2004)	Region-specific (Europe, Asia)
Production of fuels	Ecoinvent database (Version 2.2) (Faist *et al.* 2003, Jungbluth 2003, Röder *et al.* 2004)	Region-specific (Europe)
Transportation	Ecoinvent database (Version 2.2) (Spielmann *et al.* 2004)	Including road, rail, barge and transoceanic transportation
Municipal solid waste incineration	Ecoinvent database (Version 2.2) (Doka 2003)	
COT, conventionally cultivated	Ecoinvent database (Version 2.2) (Althaus *et al.* 2004)	
Energy requirement of PET fibre spinning (from resin)	0.64 kWh electricity and 5 MJ heat (from fossil fuel) based on Brown *et al.* (1996)	
Fabric use (PLA, cotton, PET)	Laundry Regime/ Process created in GaBi 4 using data from Ecoinvent database.	

5.8 Process flow for polylactic acid fabric

Figure 5.6 shows a system flow diagram for the production of PLA fabric from corn as a raw material. The scope of the inventory analysis for the production of PLA fabric is modelled using four overall phases. This includes the agricultural cultivation of corn at the farm, the production of polylactide granulate, the fabric manufacturing phase and the use phase of a 0.25kg t-shirt made from PLA. The unit processes are illustrated in Figures 5.6 to 5.10 (see Appendix 15).

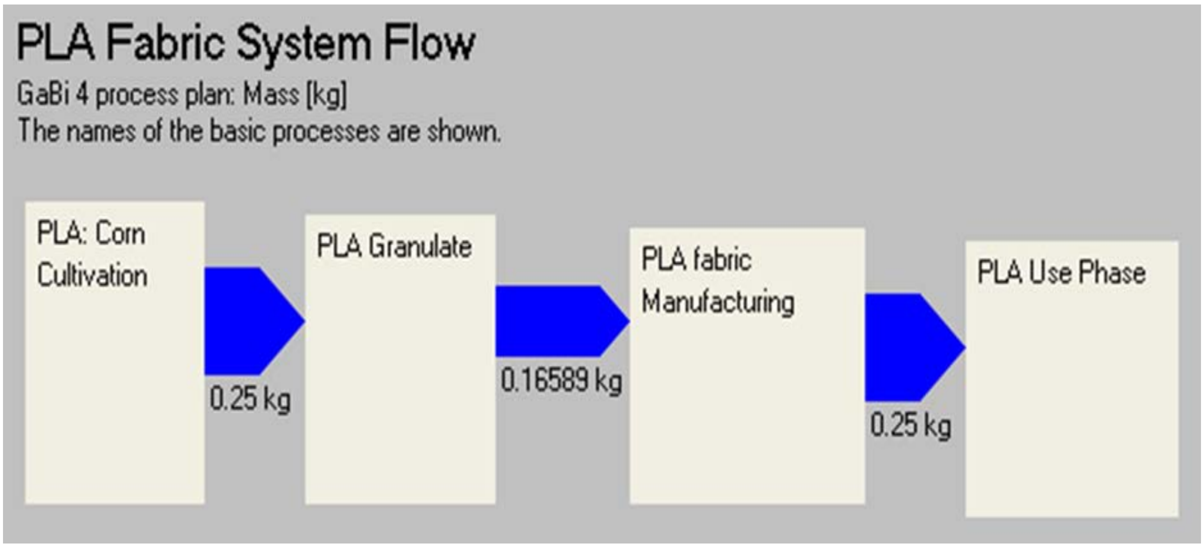

Figure 5.6: Screen shot showing the life cycle system flow for the production of 0.25kg polylactic acid fabric from corn cultivation to use phase

5.8.1 Corn cultivation at farm

A typical United States farm was considered for the country or regional specification for the cultivation of maize grains at the farm. The inventory for this unit process of agricultural production of corn at the farm is available in the ecoinvent v2.2 database. These include global average data for an inventory process of soil cultivation, sowing, weed control, fertilisation, pest and pathogen control, harvest and drying of the grains as raw material and use of diesel, machinery fertilisers and pesticides. This inventory is modelled using the functional unit of 1kg of corn grain and scaled down to account for the production of 0.25kg fabric. The unit process and input flow are illustrated in Figure 5.7.

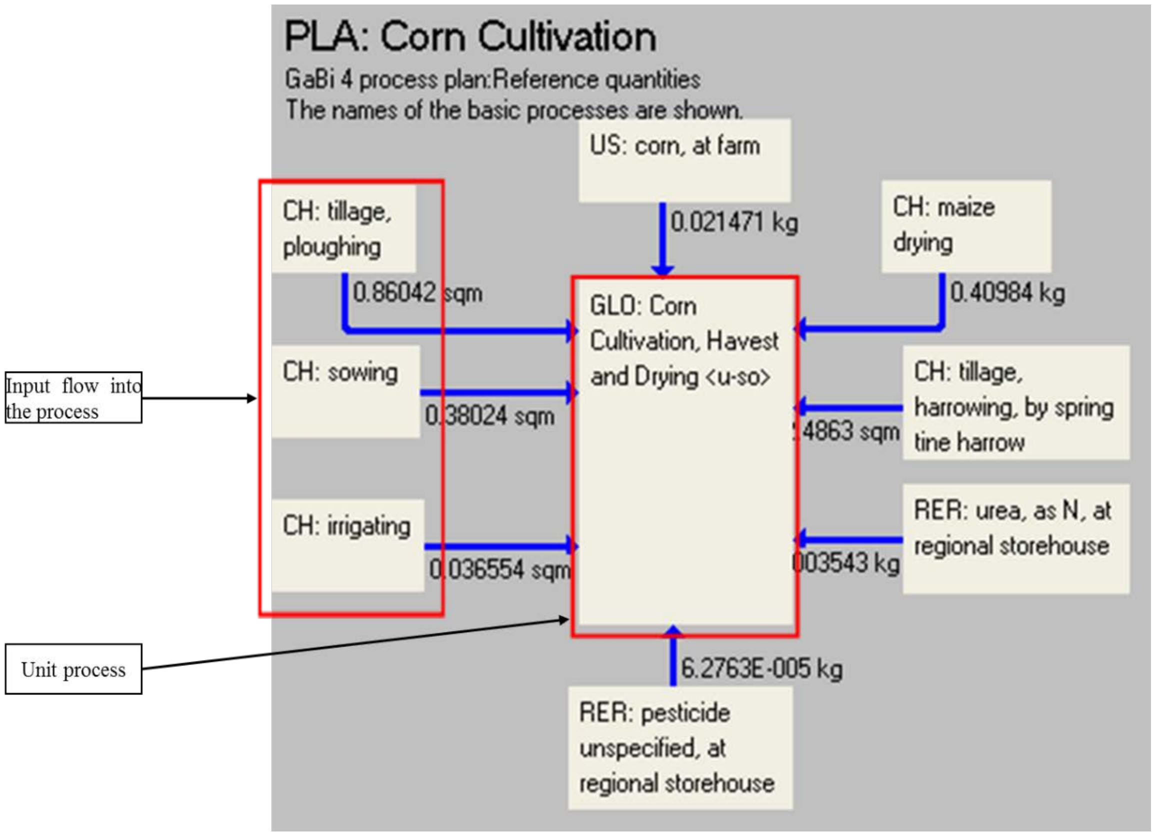

Figure 5.7: Screen shot showing the unit process and input flow for the cultivation of corn at farm modelled using GaBi 4 LCA analysis software. CH, RER (geographical code for Switzerland and Europe), u-so=unit process, single operation

The water use for the agricultural production of corn at the farm was expressed as the sum of all natural fresh water consumption. This includes water acquired from irrigation of surface (rivers and lake) and ground water as well as the unspecified natural origin. The cumulative energy demand was expressed as the total of fossil and nuclear energy. The CML2001 100-year global warming potential (GWP) for 1kg of corn produced at farm available in the ecoinvent v2.2 database was used to work out how much GWP 0.25kg will contribute.

5.8.2 Production of PLA granulate

The inventory for the manufacture of polylactide granulate at the plant used in this study refers to LCI data produced by NatureWorks LLC (Vink *et al.* 2007) and available in the ecoinvent v2.2 database. The unit process and input flow are illustrated in Figure 5.8. This inventory was carried out based on the production of 0.25kg of PLA granulates from corn at the farm. The inventory includes data used in the steps required for the manufacture of starch from maize corn (including the mechanical separation, swelling in process water, milling, and desiccation and drying) and the fermentation process which involves the use of bacteria and enzymes to obtain fermentable glucose or starch effluents. This process requires the use of energy, water, sulphur and enzymes to convert starch obtained from corn grain into dextrose syrup, corn gluten feed, meal and germ (Vink *et al.* 2003). Dextrose is then fermented to produce an intermediate dimer called lactic acid. Lactic acid can be produced by chemical synthesis or microbial fermentation. According to Abdel-Rahman *et al.* (2011), microbial fermentation offers more advantage than chemical synthesis, as the latter involves non-renewable raw materials such as corn, low production temperature and energy consumption and a highly pure lactic acid.

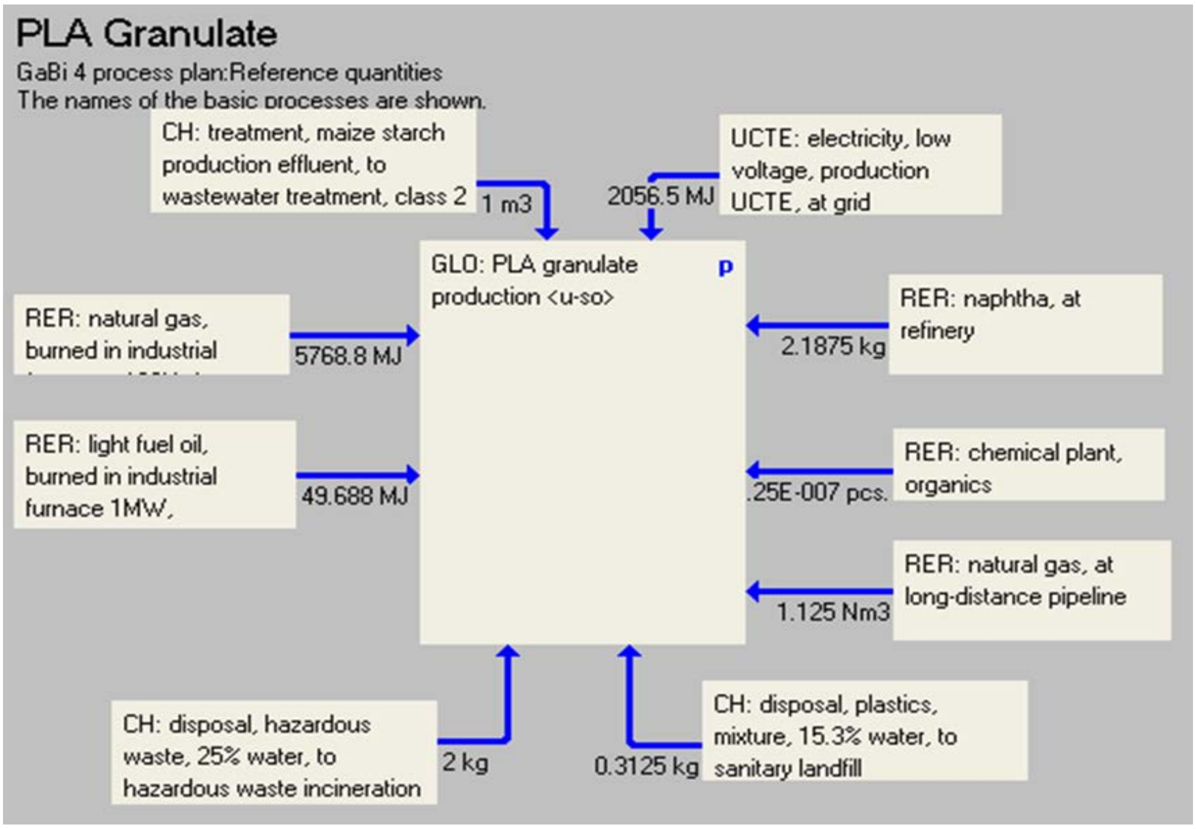

Figure 5.8: Screenshot showing the unit process, and input flow for the production of PLA granulate modelled using GaBi 4 LCA analysis software. CH, RER (geographical code for Switzerland and Europe), u-so=unit process single operation

The fermentation includes the following process: cooling water, micro-organisms, growth media (corn steep liquor from wet-milling process, yeast extract and minerals), sterilising agents, pH neutralizers, wastewater treatment, and cell and lactic acid separations (Rafael A. Auras, *et al.* 2010). The inventory takes into account the cumulative energy (fossil + nuclear) demand from the corn wet mill to the ring opening polymerization of the lactide into pellets. The CML2001 100-year global warming potential (GWP) for 1kg of PLA granulate at plant available in the ecoinvent v2.2 database was used to work out how much GWP 0.25kg will contribute. Transport is excluded from the inventory since the corn wet mill and the lactic acid plant are located on the same site (Vink *et al.* 2003).

5.8.3 PLA Fabric Manufacturing

The details of the unit process of PLA fabric manufacturing from the melt extrusion and the spinning into the fibre is found in Lim *et al.* (2008). However, for the purpose of the study the extrusion process for the plastic film available in the ecoinvent v2.2 database was used as the inventory of the production of fibres from PLA granules. This method was chosen because commercial grade PLA resin can be processed using a conventional PET extruder and extruder screw (Lim *et al.* 2008). Figure 5.9 illustrates the unit process and input flow for the manufacturing of fabrics from PLA granulate.

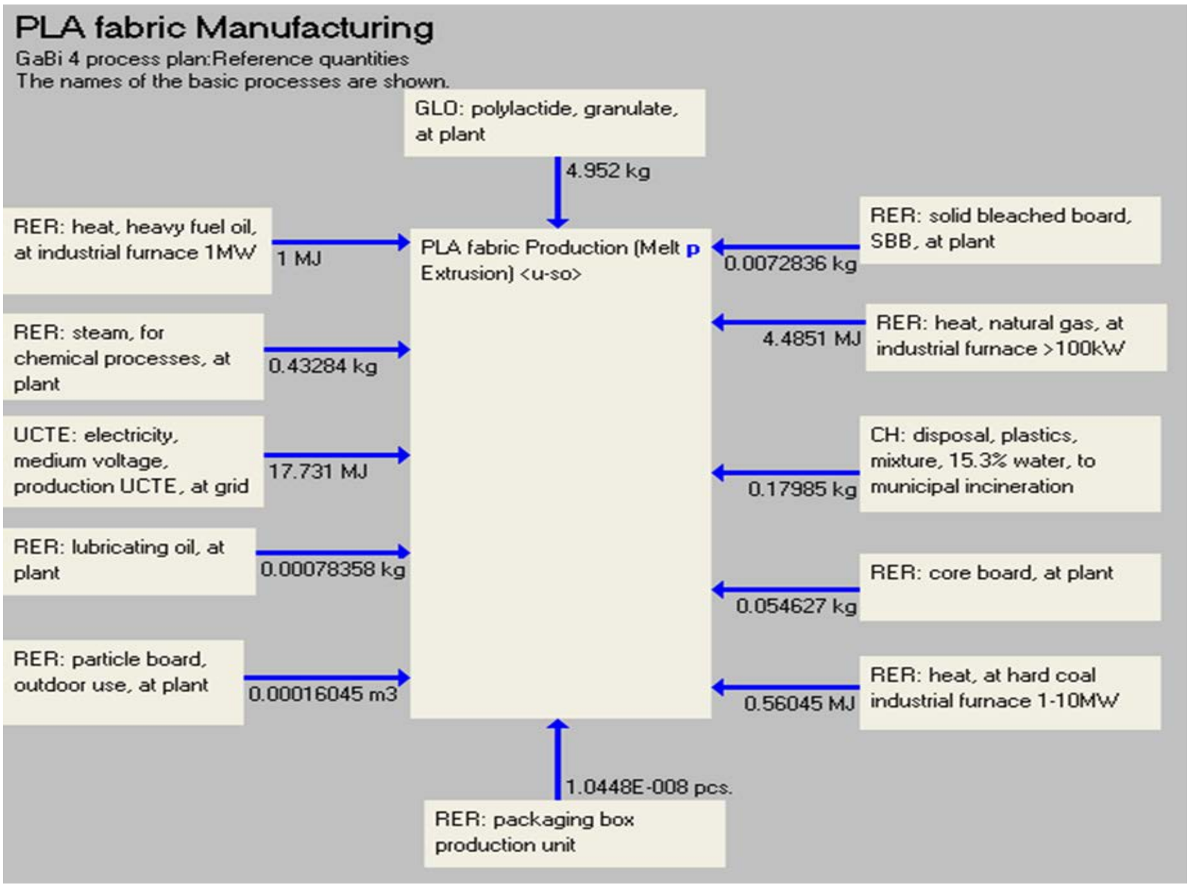

Figure 5.9: Screenshot is showing the unit process and input flow for the production of PLA fabric modelled using GaBi 4 LCA analysis software. CH, GLO, RER (geographical code for Switzerland, global and Europe), u-so=unit process single operation

The process of producing fabric or textile from PLA fibres or yarn is similar to PET. However, care was taken to avoid exceeding the transition temperature for PLA. The process involves carding and spinning; the inventory does not include any form of blending or dyeing of the fabric. The inventory of water usage for the overall process flow of PLA fabric includes process water, cooling water, irrigation of surface and the ground water.

5.9 Process Flow for PET Fabric

Figure 5.10 shows the system flow and unit process diagram for the production of PET fabric from crude oil as the starting material. The dataset covered in this section represents the ‘cradle-to-usage’ sourced from the inventory developed by PE INTERNATIONAL in GaBi 4.4 and its integrated ecoinvent database v2.2 (Frischknecht *et al.* 2007). It includes the inventory analysis of the input and output data required to produce 0.25kg of PET t-shirt. (Appendix 16).

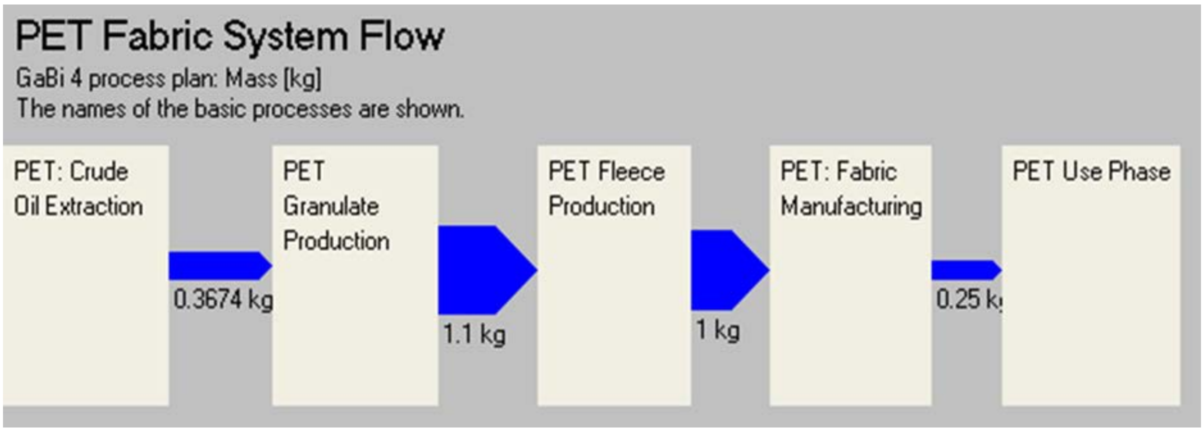

Figure 5.10: Screenshot showing the output of GaBi 4 analysis for the lifecycle system flow of the production of 0.25kg PET fabric from crude oil to use phase

Figure 5-11 shows the unit process, and input flow for the extraction of crude oil modelled using GaBi 4 analysis software. The inventory data which takes into account the energy, chemical, natural gas resource required during well drilling, crude oil production and processing is based on industry data such as the Eco-profiles of the European plastic industry (Hischier 2007).

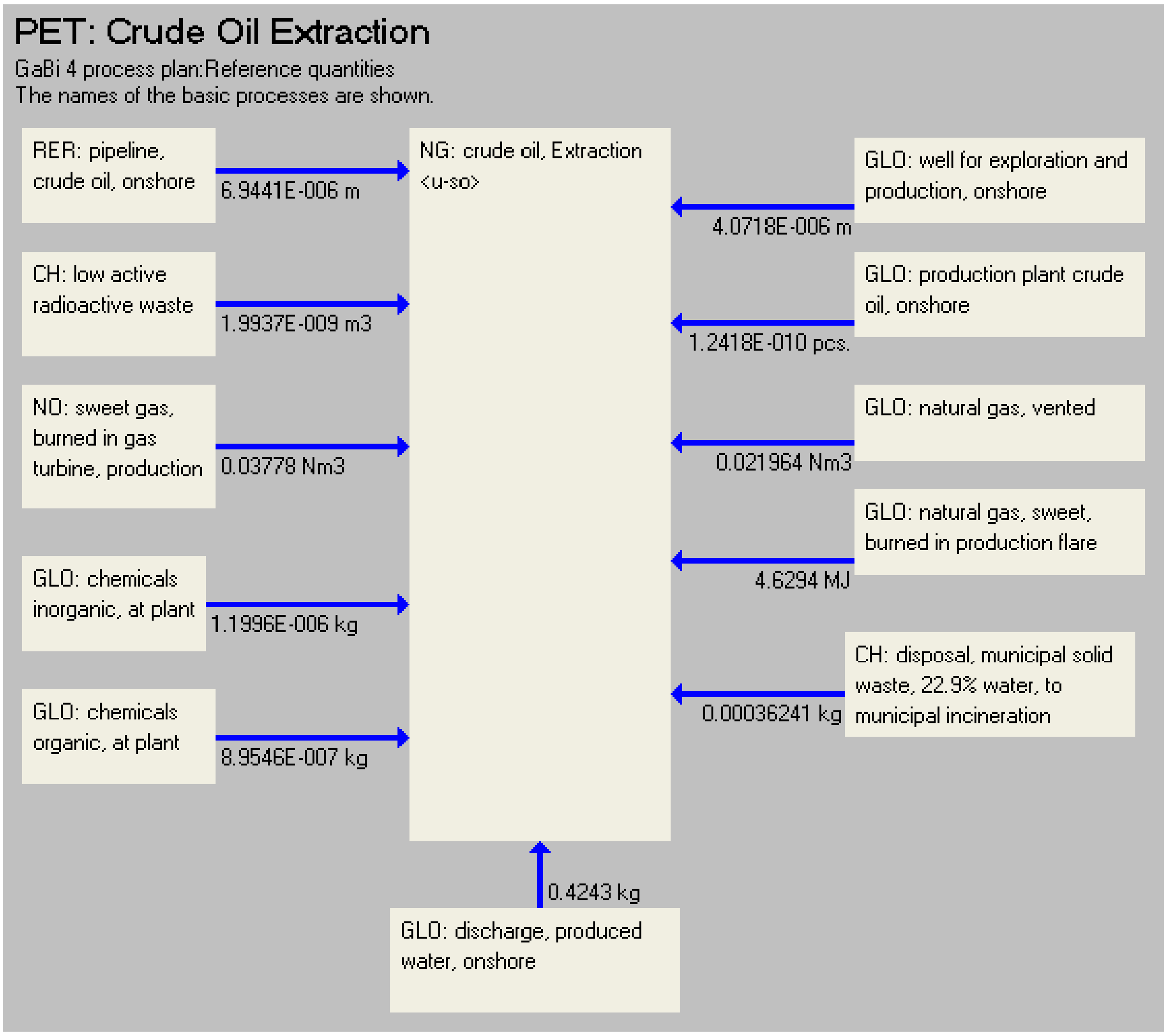

Figure 5.11: Screenshot showing the unit process and input flow for the crude oil extraction and refinery modelled using GaBi 4 LCA analysis software. CH, GLO, RER (geographical code for Switzerland, global and Europe), u-so=unit process single operation

The basic material for the production of PET fabric is polyethylene terephthalate (PET) granulate. This unit process (Figure 5.12) includes material and energy inputs, waste and emissions to the air, land and water, and the extraction to polyethylene HDPE granulate. High-Density Polyethylene is produced by the polymerisation of ethylene, which is then extracted in a steam cracker using naphtha or gas oil. The polymerised ethylene is then passed through a low-pressure process to produce HDPE granules.

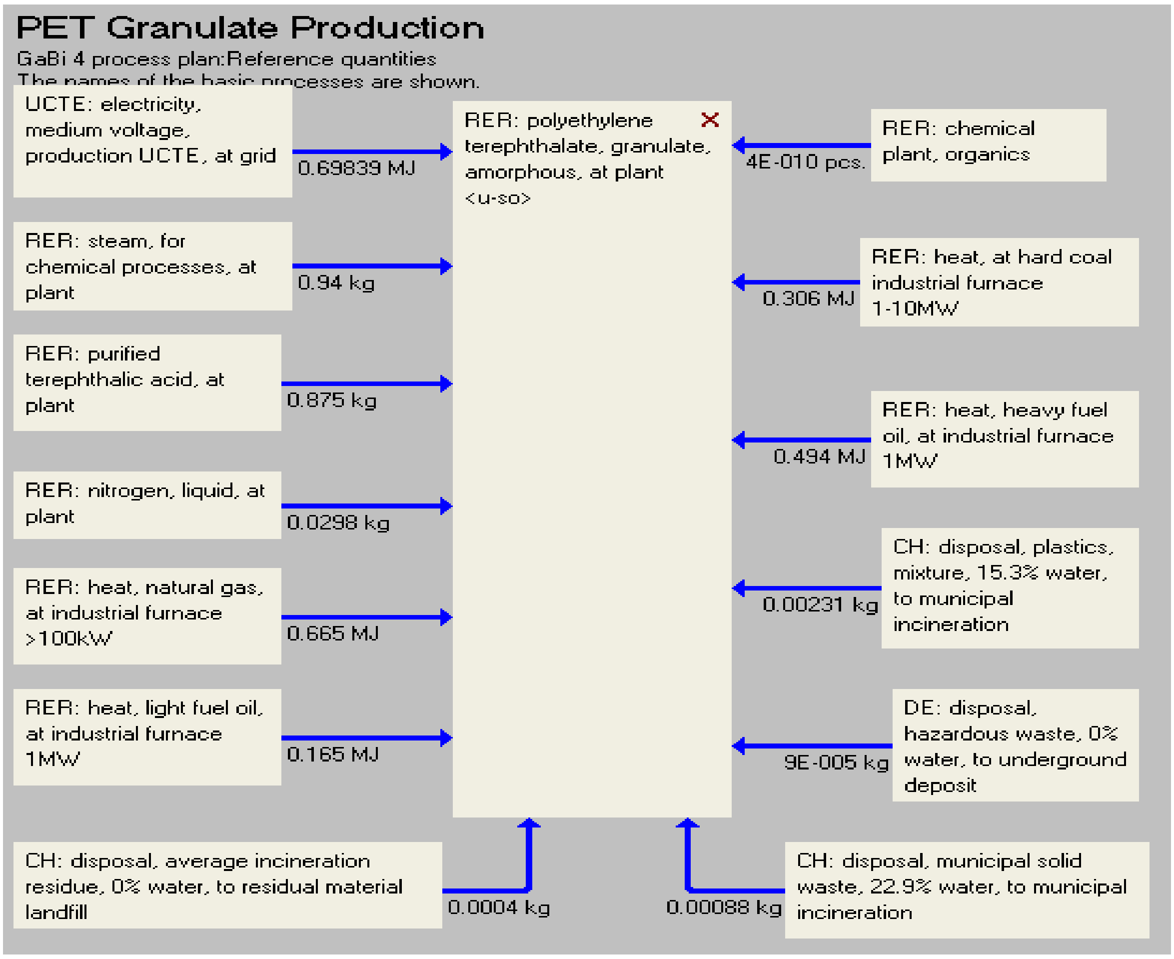

Figure 5.12: Screen shot showing the unit process and input flow for the production of PET granulate modelled using GaBi 4 LCA analysis software. CH, GLO, RER (geographical code for Switzerland, global and Europe), u-so=unit process single operation

The background system for these unit processes involves electricity, thermal energy, steam and the refinery products. The average data for the production of 0.25kg amorphous polyethylene terephthalate granulate showing the input and output materials, the cumulative energy demand of 43.3 MJ and water usage is shown in Appendix 16. The data is based on the average unit process from the Eco-profiles of the European plastic industry (Hischier 2007). For the production of PET fabric (Figure 5.13), it was assumed that there is a technical equivalent of cotton and PET when used as fibres in the manufacture of fabrics for clothes. Therefore, this study adopts a similar process and inventory used for the production of cotton.

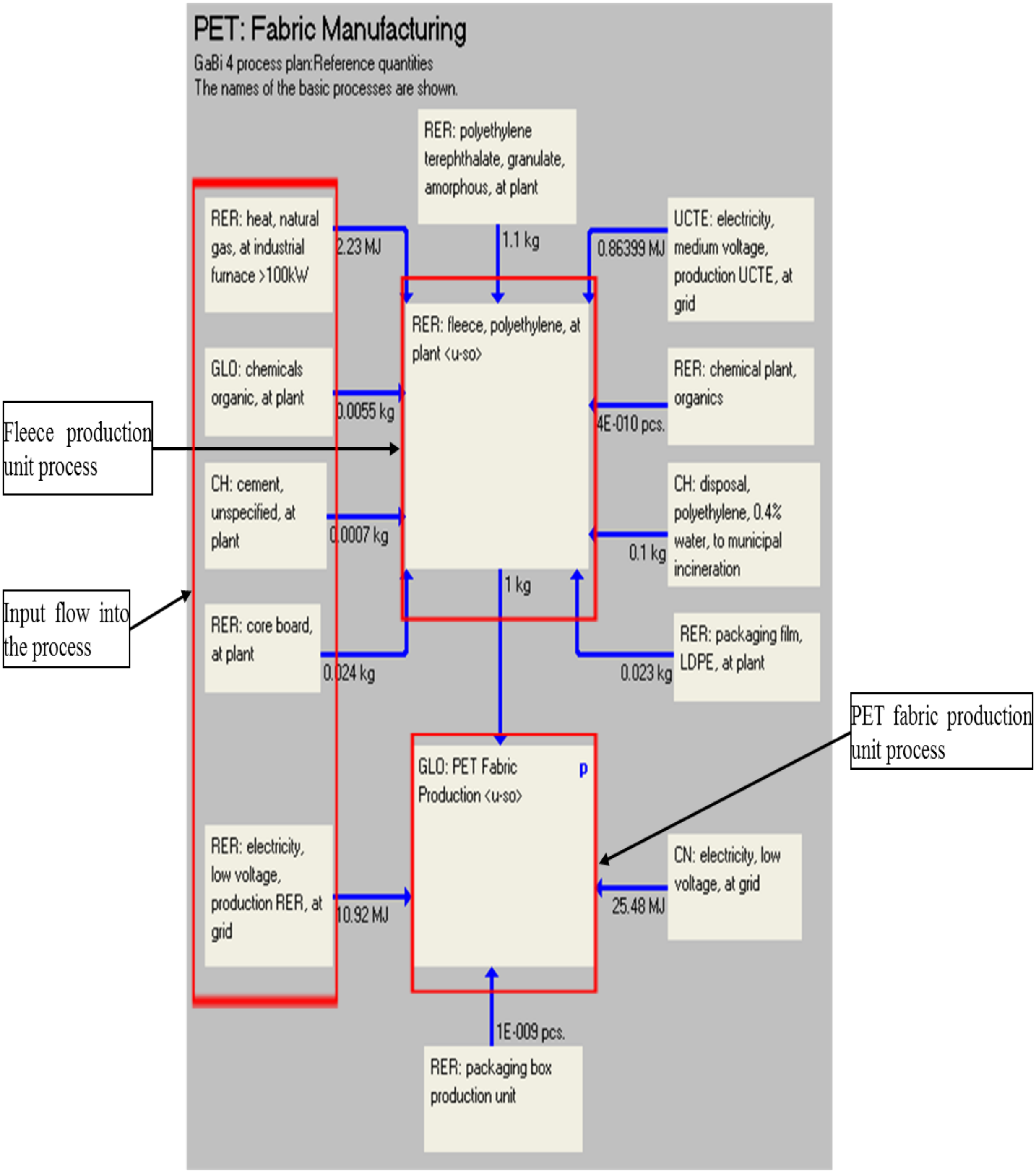

Figure 5.13: Screen shot showing the unit processes and input flow for the production of polyethylene fleece and PET fabric modelled using GaBi 4 LCA analysis software. CH, GLO, RER (geographical code for Switzerland, global and Europe), u-so=unit process single operation

5.10 Process flow for cotton fabric

Figure 5.14 shows the system flow diagram for the manufacture of cotton fabric. The inventory of cotton fabric (Appendix 17) used in this study is based on the global average (US, China, Switzerland and Europe) dataset developed in the ecoinvent database v2.2 (Frischknecht *et al.* 2007). This represents about 43% of the world's cotton production as at 2005 (Shen and Patel 2008). The inventory initially referred to the production of 1kg fabric from which the input and output for 0.25kg were calculated. The overall inventory data comprises the unit processes of fibre production, knitting and weaving, textile manufacturing and use phase. The inventory takes into account all the input materials while at the farm, including transport, fuel consumed in the field for operations (e.g. equipment) and all direct emissions to air from the combustion of the fuel, harvesting and production of the 0.25kg cotton fabric.

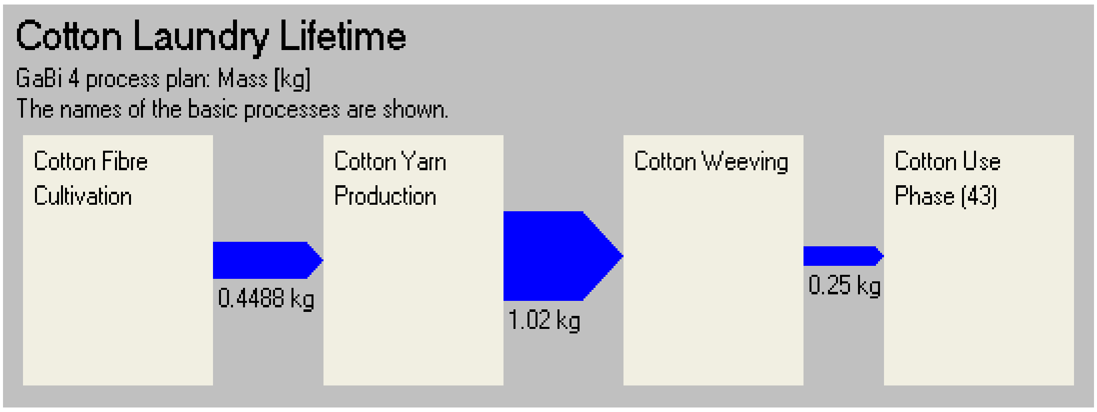

Figure 5.14: Screen shot showing the output of GaBi 4 analysis for the lifecycle system flow of the production of 0.25kg cotton fabric from fibre cultivation to use phase

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5.10.1 Production of cotton fibre

The inventory for the manufacture of cotton fibre is a multi-output process involving the agricultural production (cultivation, pest and pathogen control, irrigation, harvesting and ginning, processing of cottonseed, production of cotton fibres at the farm), and the production of fibres at the farm. This process has an economic allocation of 87.2%, due to the co-production of fibres and the cottonseed at the farm (Nemecek *et al.* 2007). Agricultural infrastructure, manufacturing of farm equipment and farm buildings are not included in this inventory. The system flow diagram for the single operation unit process of cotton fibre cultivation is shown in Figure 5.15.

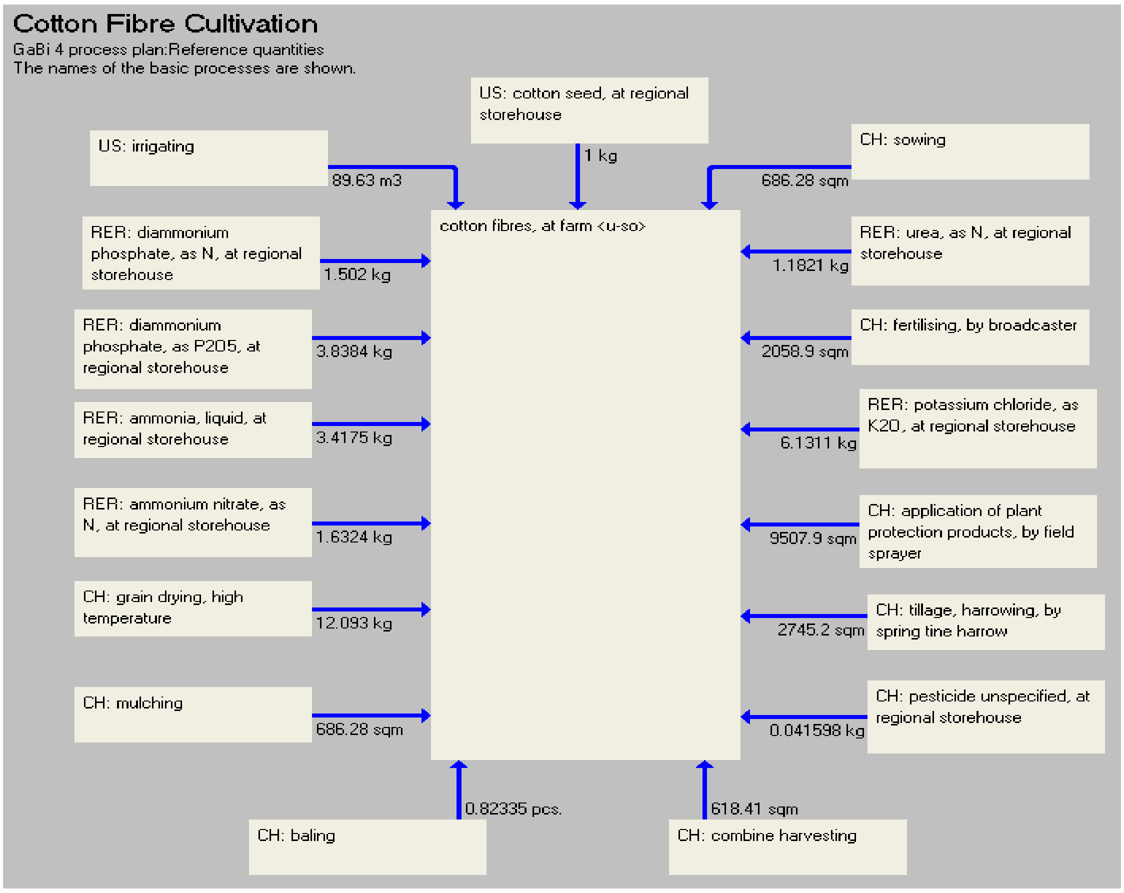

Figure 5.15: Screen shot showing the unit processes and input flow for the cultivation of cotton fibre modelled using GaBi 4 LCA analysis software. CH, US, GLO, RER (geographical code for Switzerland, USA, Global and Europe), u-so=unit process single operation

5.10.2 Production of cotton yarn

For the production of cotton yarn (Figure 5.16), the inventory includes energy consumption, transport, carding and spinning of the lint cotton into yarn. It is assumed that mechanical cleaning is used with no chemicals involved (Althaus *et al.* 2007). This inventory is linked to the weaving of cotton fabric by the process of textile yarn production and weaving. The data represents the global value for the combination of two-unit processes, the processing of lint cotton into yarn and yarn refining. Processing 1kg lint cotton includes cleaning (no chemical cleaning), carding and spinning which are the primary procedures. The process requires energy, transport and infrastructure. The central processes of refining of 1kg cotton yarn are bleaching, washing, and drying, no dyeing. This study does not include inventory for the process of dyeing since the sample used is pure, undyed cotton fabric. These processes involve energy consumption, material needed for refinement and wastewater treatment (Althaus *et al.* 2007).

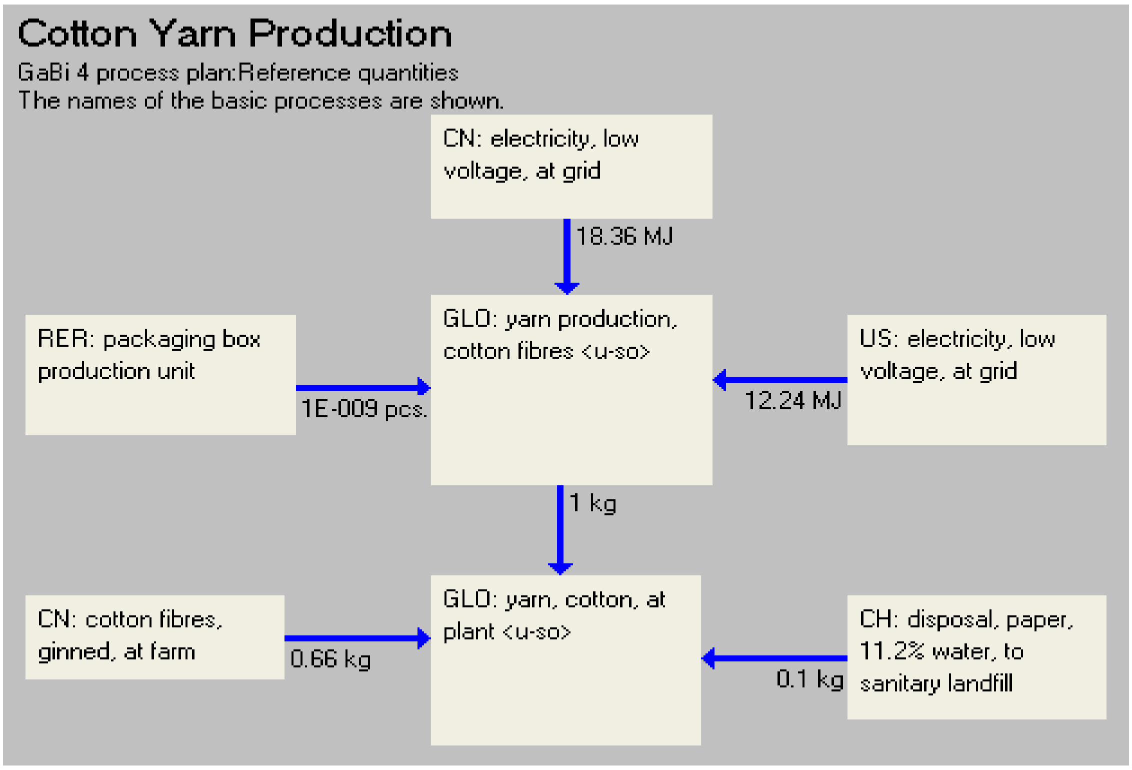

Figure 5.16: Screenshot is showing the unit processes and input flow for the cultivation of cotton fibre modelled using GaBi 4 LCA analysis software. CH, US, CN, GLO, RER (geographical code for Switzerland, USA, China, Global and Europe), u-so (unit process single operation)

5.10.3 Fabric Weaving Production

The inventory for cotton weaving represents a global average from mills in the USA, China and Europe. The data collected includes bale opening, yarn preparation, spinning and weaving. The data elements for the weaving of cotton yarn into the textile includes the raw materials inputs and outputs energy consumption by source, packaging, wastes and emissions for the weaving of 0.25kg of cotton calculated from a single operation unit process for 1kg production baseline (Figure 5.17). The data was obtained from the ecoinvent database as collated from the literature (Althaus *et al.* 2007).

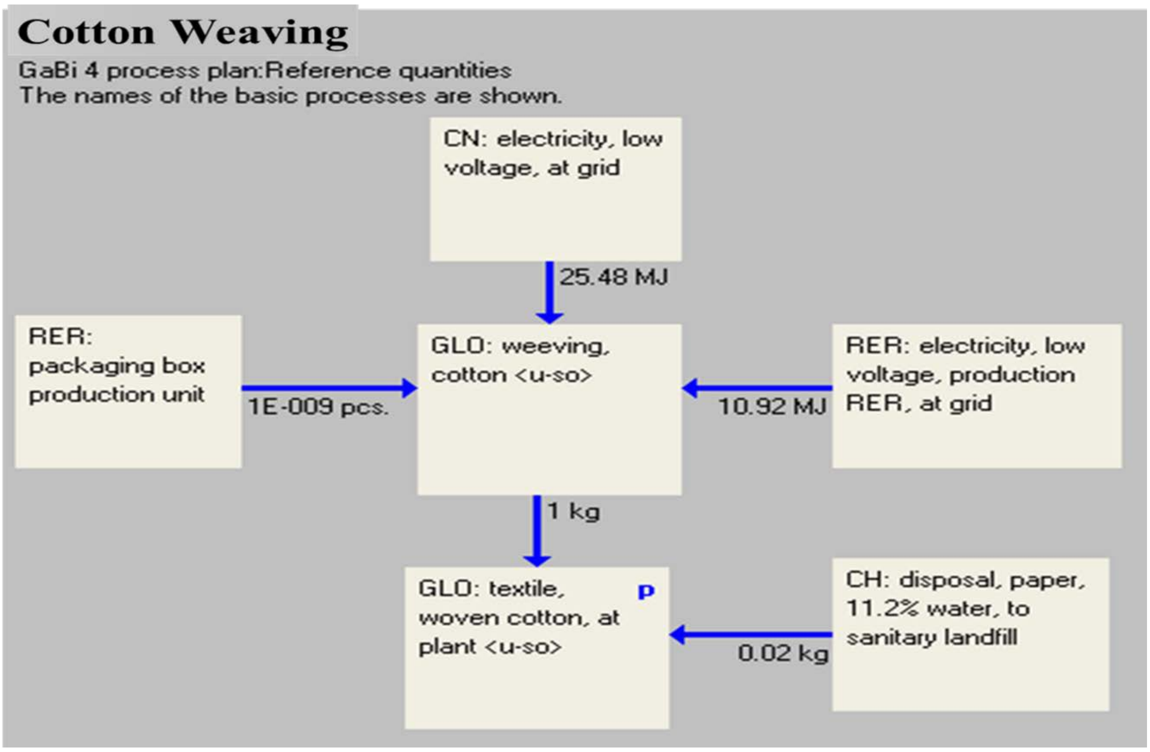

Figure 5.17: Screenshot is showing the unit processes and input flow for the weaving of cotton fabric modelled using GaBi 4 LCA analysis software. CH, US, CN, GLO, RER (geographical code for Switzerland, USA, China, Global and Europe), u-so (unit process single operation)

5.11 Inventory for laundry use phase of PLA, PET and cotton t-shirt

Figure 5.18 shows an example of the model for the laundry use phase of one wash cycle for all fabric samples. It was necessary to model the use phase for PLA, PET and cotton in this study using data and characterisation of appliances, detergent and user behaviour relating to the UK environment and consumer behaviour. The importance of this refers to the fact that user behaviour is an imperative factor in the environmental impact of fabric use. The study assumed that the emissions from the use phase would be similar for all three fabrics due to the mixed mode laundry method. Therefore, the production of detergent, washing machine and other infrastructure associated with manufacturing were excluded from the inventory. The scope of the use phase is limited to the number of laundry cycles the fabric can withstand before any significant impact is noticed in the mechanical properties. The number of laundry cycles was obtained using post hoc pairwise comparison analysis described in Section 3.4. Other inventory data applicable to this stage includes energy, water and quantity of detergent used per wash cycle. An example of the model calculation showing the inventory parameters, formula and value are shown in Figure 5.19.

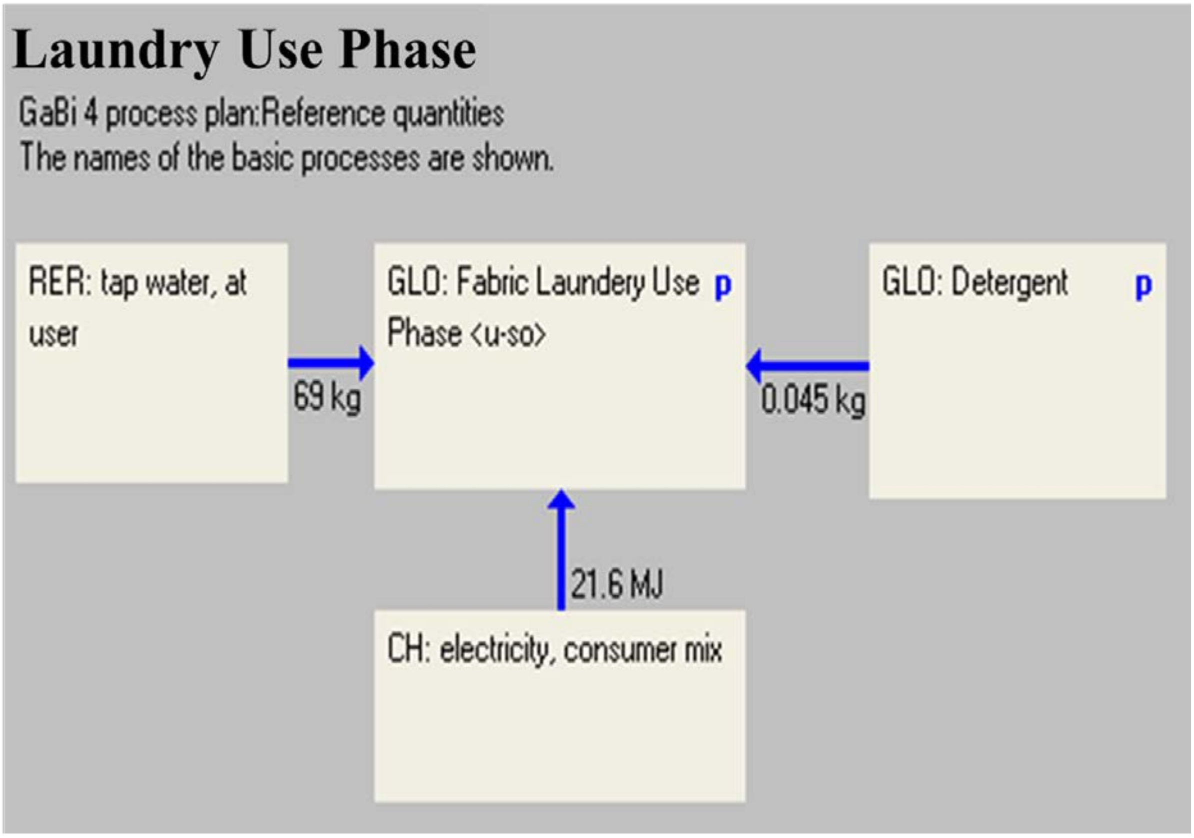

Figure 5.18: Screen shot showing the unit processes and input flow for the use phase of one laundry cycle modelled using Gabi 4 LCA analysis software. CH, GLO, RER (geographical code for Switzerland, Global and Europe), u-so (unit process single operation)

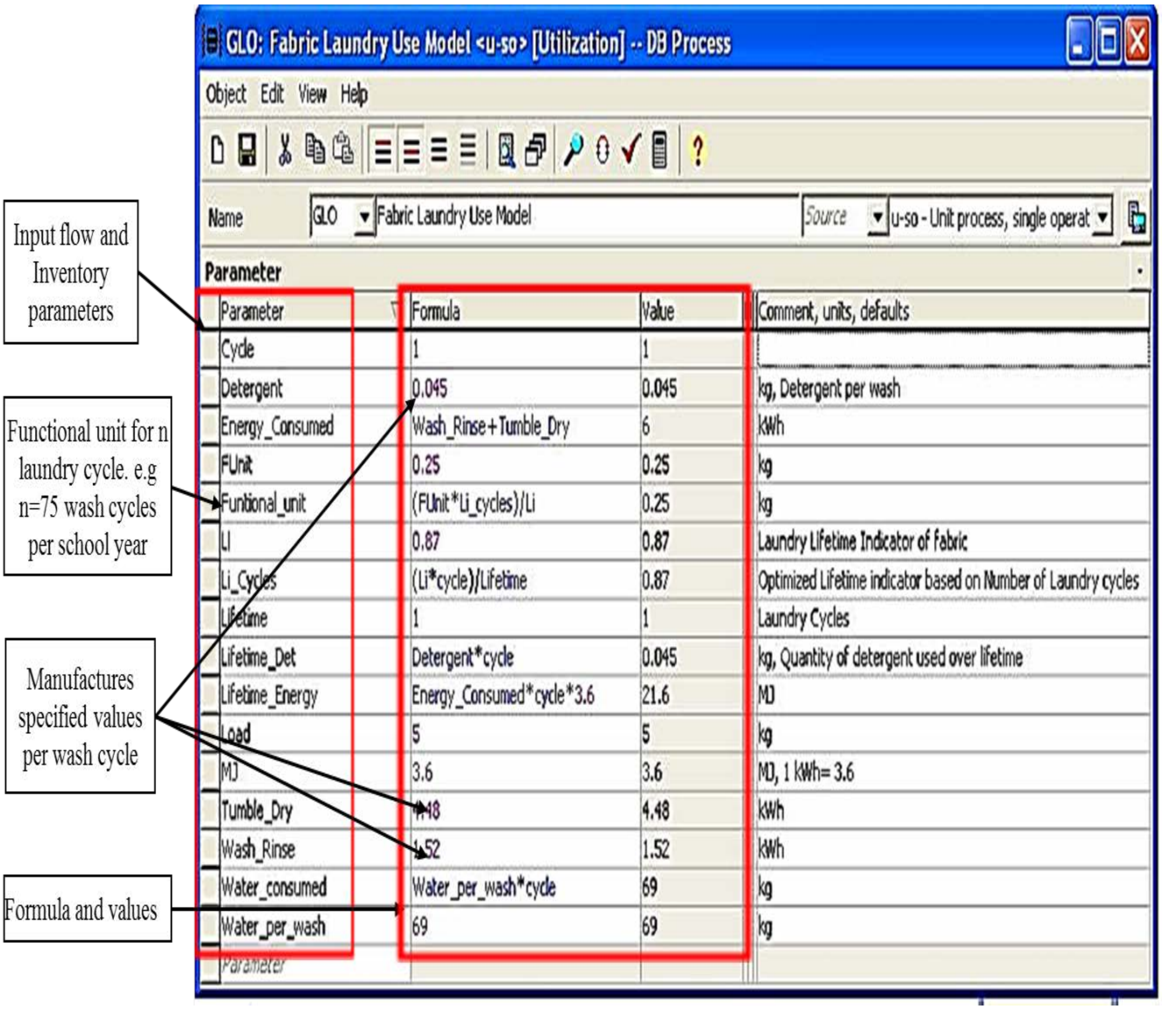

Figure 5.19: Screen shot showing the laundry use phase parameters and calculations. The wash/rinse, tumble dry and water per wash are values specified by the washing machine and tumble dryer manufacturer. The quantity of detergent used per wash (0.045kg) as specified by the manufacturer

5.12 Life Cycle Impact Assessment

5.12.1 Water Demand

The inventory of resources used in this process includes water use which takes into account original and natural fresh water consumption. This includes irrigation of surface and groundwater, river, lake and unspecified natural sources for the agricultural production of cotton. The water usage during the production of cotton fibre at farm takes into account water used to cool the machines and turbine, as well as other unspecified natural sources. The choice of these categories of water usage is based on the different impact they have on the environment. For example, irrigation water depletes local availability of surface or ground water, while the use of surface water for irrigation causes salinization (Kooistra *et al.* 2006) depending on the management and environment. The unit of water usage was given in kg using a conversion factor of $1m^3 = 1000kg$. The overall water consumption during the production of fabric from yarn takes into account the process, turbine and cooling water from unspecified natural sources.

5.12.2 Global Warming Potential Calculation

The GWP is a measure of the greenhouse effect of gas for example; CO_2, N_2O and CH_4 expressed in terms of CO_2 (kg CO_2-eq.) equivalent emissions. The GWP is calculated by deducting the CO_2 sequestrated during cultivation of agricultural products from the total CO_2-eq emitted during the whole process. This method is appropriate where the availability and accuracy of the biogenic CO_2 of the product are verified (Palstra and Meijer 2010). Also, where there are non-agricultural products (such as PET in this study), this method cannot be applied. An alternative method used in this study is deducting the bio-based carbon in the product from the fossil CO_2 emission (Shen and Patel 2010). This approach is suitable when comparing the CO_2 emission of corn and cotton with petroleum-based PET in accordance with the ISO 14044 standard (ISO 2006). Since this study is only cradle-to-usage and not ‘to the grave’ the bio-based carbon is still active throughout the life cycle of the product until it reaches its end-of-life at which point the bio-based carbon is released again, and the cycle closes (Shen and Patel 2010).

From the pilot experiment and load-extension analysis, PLA and cotton showed a significant effect of the laundry regime at 10 laundry cycles, while PET retains its properties beyond 50 laundry cycles. However, during the main experiment, different laundry treatments were introduced. Consequently, a durability and life time indicator was calculated for each fabric based on the laundry treatments, tensile properties and the number of the laundry cycles where the fabrics showed significant changes in their tensile properties. The result was then incorporated into the LCA model as the lifetime wash cycle.

5.12.3 Durability and Lifetime Indicator

In the environmental assessment carried out by Kalliala (1997), the lifetime of bed-sheets was estimated by a tensile property and abrasion durability test. Therefore, the fabric durability was evaluated using the results of the mechanical properties. A Tukey multiple comparison was performed (Appendices 11, 12 and 13) to identify the laundry cycles that indicated the significant ($p<0.05$) change in the tensile properties of the fabrics from the unwashed during the laundry regime. Table 5.3 shows the result obtained from the pairwise comparison.

Table 5-3: Number of laundry cycles where fabrics showed significant changes to laundry treatments ($p<0.001$)

Laundry Treatments	PLA			PET			Cotton		
	Tensile Modulus	Tensile Strength	% Extension	Tensile Modulus	Tensile Strength	% Extension	Tensile Modulus	Tensile Strength	% Extension
DT	30	10	1	50	30	6	3	1	1
DA	10	6	50	50	3	10	1	1	1
DSA	50	1	6	6	6	50	1	1	1
DST	50	30	30	50	1	30	1	1	1

For the fabrics washed in DT laundry treatment, PET showed a better tolerance to the laundry regime than PLA and cotton. PET showed significant changes in its tensile modulus, tensile strength and percentage extension after 50, 30 and six laundry cycles. Whereas, PLA endured 30, 10 and one laundry cycles before showing any changes in its tensile modulus, tensile strength and percentage extension. Cotton fabric sustained significant changes to its tensile modulus, tensile strength and percentage extension after three, one and one laundry cycles respectively.

5.12.4 Fabric Lifetime Indicator

The lifetime indicator was calculated for each fabric based on the tensile modulus, tensile strength and percentage extension results (Appendix 14) of the laundry cycles and laundry treatments in Table 5.3. For this analysis, the results of the unwashed fabrics were considered as the reference point. The lifetime indicator (Li) for each material was calculated using Equation 5 and 6:

$$Li_{fabric} = Average\ Tensile\ Properties\ (TMi, TSi, PEi)$$

Equation 5

$$Tensile\ Properties\ (TMi, TSi, PEi)\ lifetime\ indicator\ = \frac{Average(\mathrm{DT, DA, DSA, DST})}{\mathrm{Unwashed}}$$

Equation 6

Where:
Li_{fabric} = Lifetime indicator of fabric
TMi = Tensile modulus lifetime indicator
TSi = Tensile strength lifetime indicator
Pei = Percentage extension lifetime indicator

Using this calculation method, the lifetime indicator Li for each fabric is represented in Table 5.4. According to Agarwal *et al.*, the life cycle of a garment during use was considered to be 40 laundry cycles (Agarwal *et al.* 2011b). Therefore, the lifetime indicator was expressed in number of laundry cycles by multiplying with 40 laundry cycles (Table 5.4). This calculation was based on the assumption that the lifetime of the fabrics is proportional to the tensile properties and number of laundry cycles.

Table 5.4: Lifetime indicator and number of laundry lifetime for each fabric

	TMi	*TSi*	*Pei*	*Li*	*Number of washes*
PLA	0.98	0.71	0.93	0.87	35
PET	1.07	1.06	0.99	1.04	42
Cotton	0.78	0.86	1.56	1.07	43

The result in Table 5.4 suggests that from the experimental laundry regime, 0.25kg of PLA, PET and cotton t-shirt will have a laundry lifetime of 35, 42 and 43 wash cycles. This was incorporated into the life cycle modelling.

5.13 Life Cycle Impact Assessment (LCIA)

The results presented in this section focus on the cradle-to-usage environmental performance of PLA, PET and cotton. The potential energy requirement (PED), water usage and greenhouse gas emission (GHG) impact categories are used to assess the significance of PLA as a substitute for PET and cotton fabric. The result of this LCA assumes that the environmental performance of the use phase would be similar for all three fabrics. This is because all materials were washed together (~5kg load), using similar quantities of detergent, water and energy. Based on the results discussed in Chapter 4, the scope of the use phase is limited to the number of laundry regimes that the fabrics can withstand before any significant effect is noticed in the behaviour or mechanical properties.

5.14 Laundry Lifetime Impact Assessment

5.14.1 Cumulative Energy Demand

Figure 5.20 shows the cradle-to-usage cumulative energy demand for the laundry lifetime of PLA, PET and cotton fabric. The cumulative energy demand was expressed as the total non-renewable resource of fossil and nuclear energy. The results of the assessment showed that during its laundry lifetime, PLA fabric required about 2192 MJ, followed by 2860 MJ for PET and 2,982 MJ for cotton. This implies that the overall energy demand for PLA during its life cycle is lower than PET and cotton of the same mass. However, as shown in Table 5.4, PLA had the lowest lifetime number of laundry cycles. The slight difference in energy consumption between PET and cotton could be due to the close comparison in the number of laundry cycles during their lifetime.

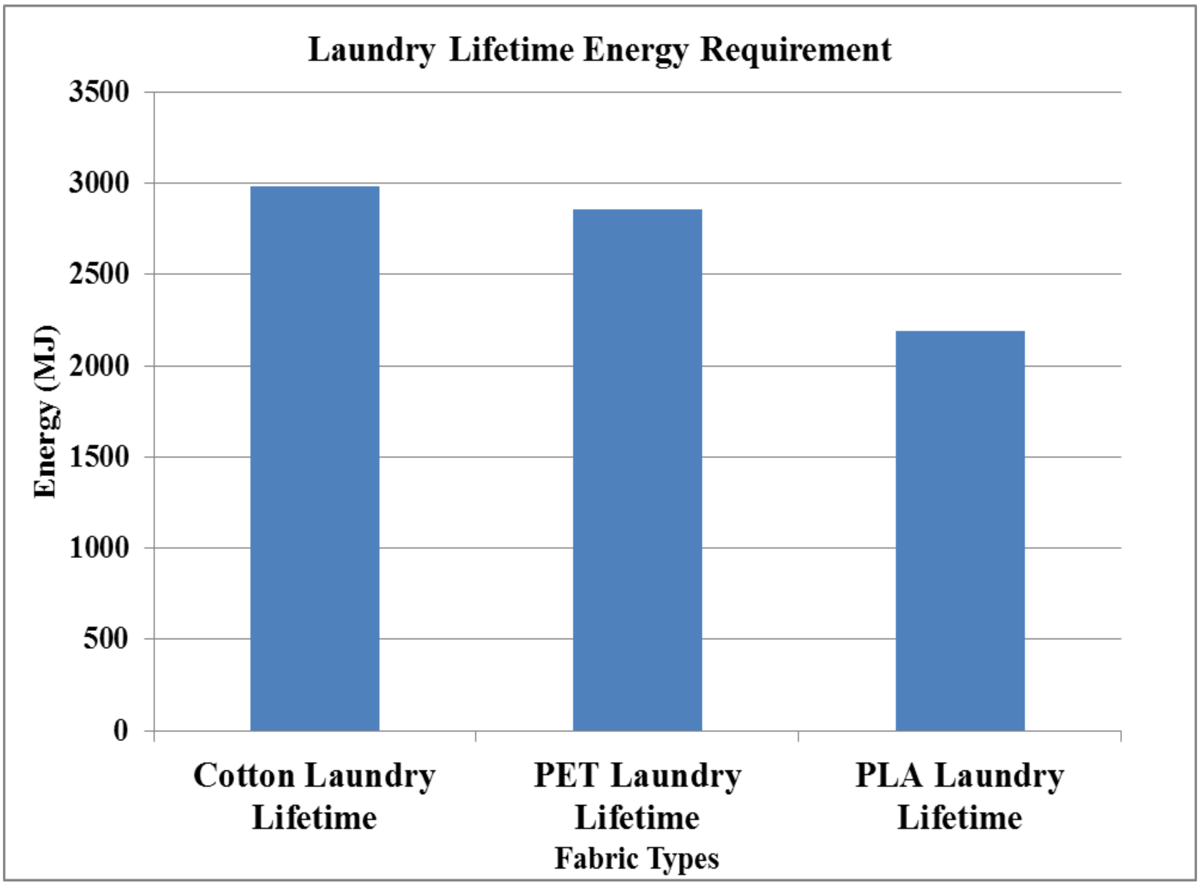

Figure 5.20: Cradle-to-usage cumulative energy demand for 0.25kg of PLA, PET and Cotton fabric during their lifetime of 35, 42 and 43 laundry cycles respectively

5.14.1.1 PLA Energy Demand

The use phase of the laundry lifetime was the main energy-intensive process during the lifetime of PLA fabric (Figure 5.21). It represented 99% of the total energy demand from cradle-to-usage. This is because the energy required during corn cultivation (1.37 MJ), production of granulate (7.58 MJ) and fabric manufacturing (2.08 MJ) is fixed throughout the lifetime of the fabric. However, the laundry lifetime of 35 wash cycles for PLA (2181.80 MJ) accounts for the use phase being the most energy-intensive process of the life cycle. This result matches that of Van Hoof *et al.*(2003) and A.I.S.E. (2013) who found that the energy requirement during the use phase exceeds 50-70% of the total energy demand for the life cycle. The majority of the energy demand is linked to the production of electricity consumed by the washing machine and heating of water for laundry (Koerner *et al.* 2011). Table 5.5 shows the energy categorised by the fuel type for each phase of the PLA fabric system. The primary fuel used in the laundry life cycle of the PLA system is coal and natural gas. This is due to the electricity used in running the washing machine and the dryer generated from coal and natural gas. Coal and natural gas generate 28% and 29% of the electricity used in the UK (Department of Energy and Climate Change 2015). Petroleum is the largest energy source during corn cultivation due to the use of diesel to run the farm equipment. As illustrated in Figure 5.21, the energy demand for the other processes in fabric manufacturing, production of lactide and granulate, and cultivation of corn is relatively small compared to the use phase.

Table 5.5: Energy Profile for PLA fabric during the laundry lifetime of 35 wash cycles (MJ)

Energy resources	Corn Cultivation	PLA Granulate	PLA Fabric Manufacturing	Laundry Use Phase
Petroleum	0.69	0.37	0.21	79.22
Coal	0.48	1.41	0.71	799.28
Natural gas	0.09	4.28	0.58	724.36
Nuclear	0.11	1.52	0.58	578.94
Total	1.37	7.58	2.08	2181.80

5.14.1.2 PET Energy Demand

Similar to PLA, the main energy demanding stage is the use phase of PET fabric. Figure 5.21 show that 92% of the total energy demand during the lifetime of PET fabric is attributed to its laundry use. This result is also consistent with that of (A.I.S.E. 2013), which found that the energy requirement during the use phase exceeds 50-70% of the total energy demand for the lifecycle. The next energy intensive process after the use phase relates to the yarn and fabric manufacturing process, 4.6 % followed by the granulate production 2.31% of the total energy demand (Figure 5.21). This is also similar to the results of Cartwright *et al.* (2011). The other processes and phases (Crude oil and PET fleece production) demand relatively less than 1% (Table 5.6). However, they should also be taken into account for their contribution to the total energy. Table 5.6 shows the energy categorised by the fuel type for each phase of the PET fabric system. The primary fuel used in the laundry life cycle of the PET system is coal and natural gas. This is due to the electricity used in running the washing machine and dry generated from coal and natural gas. Coal and Natural gas generate 28% and 29% of the electricity used in the UK (Department of Energy and Climate Change 2015). Petroleum is the largest energy source for oil extraction and production of granulate (Table 5.6). This is due to the energy of material resource requirement that is included in these phases (Franklin Associates 1993).

Table 5.6: Energy Profile for PET fabric during the laundry lifetime of 35 wash cycles (MJ)

Energy resources	Crude Oil Extraction	Granulate Production	Fleece Production	Fabric Manufacturing	Laundry Use Phase
Petroleum	16.87	29.05	1.81	9.12	96.86
Coal	0.02	5.53	1.41	96.34	964.88
Natural gas	2.66	26.16	4.31	9.58	871.95
Nuclesr	0.01	5.35	1.59	16.54	700.54
Total	19.56	66.09	9.12	131.58	2634.23

5.14.1.3 Cotton Energy Demand

Similar to PLA and PET, the major energy demand during the life cycle of cotton was attributed to the use phase. Figure 5.21 show that 90.4% of the total energy demand is linked to the electricity consumed by the washing machine and heating of water for laundry during the use phase (Cartwright *et al.* 2011, McCoy 2011). The majority of the energy demand is linked to the production of electricity consumed by the washing machine and heating of water for laundry (Koerner *et al.* 2011, McCoy 2011). The next most energy intensive process after the use phase relates to the cotton yarn and fabric manufacturing process that consumed about 4.5% of the total energy demand during the life time of the cotton fabric (Figure 5.21). The energy consumption during the fibre cultivation phase was less than 1%. Table 5.7 shows the energy categorised by the fuel type for each phase of the cotton fabric system. The primary fuel used in the laundry life cycle of the PET system is coal and natural gas. This is due to the electricity used in running the washing machine and the dryer generated from coal and natural gas. Coal and Natural gas generate 28% and 29% of the electricity used in the UK (Department of Energy and Climate Change 2015). Petroleum dominated the energy source during fibre cultivation due to the use of diesel to run the farm equipment. While electricity generated from coal dominated the energy required during the yarn and fabric production.

Table 5.7: Energy Profile for cotton fabric during the laundry lifetime of 35 wash cycles (MJ)

Energy resources	Fibre Cultivation	Yarn Production	Fabric Manufacturing	Laundry Use Phase
Petroleum	6.26	14.99	9.13	99.16
Coal	2.38	88.28	96.34	987.86
Natural gas	3.92	17.60	9.58	892.71
Nuclesr	2.26	18.03	16.54	717.21
Total	14.82	138.90	131.59	2696.95

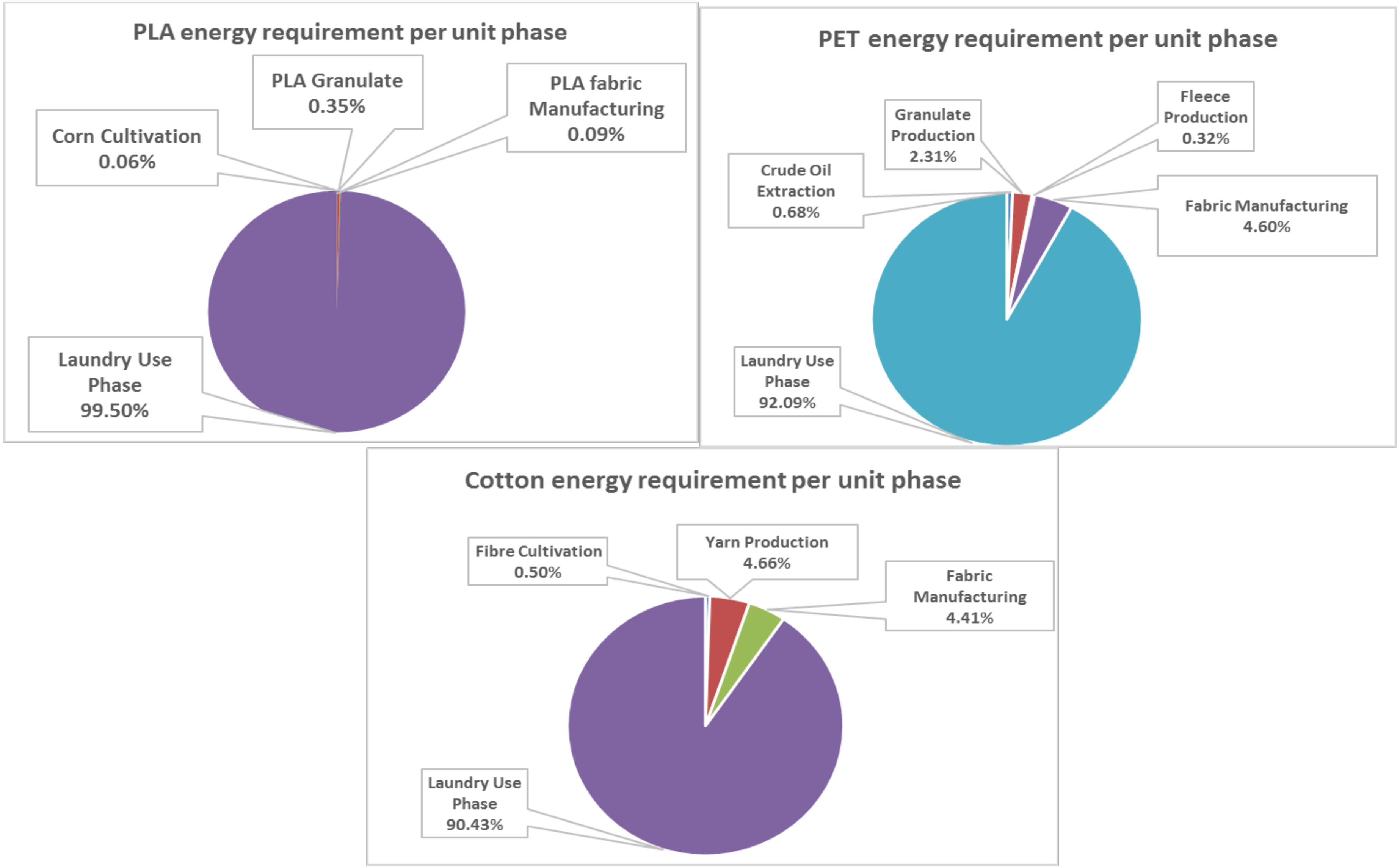

Figure 5.21: Breakdown of the energy demand per unit process for the cradle-to-usage (laundry lifetime) of 0.25kg PLA, PET and Cotton t-shirt. Energy requirement is fixed for other phases except the laundry use phase. This accounts for the high percentage during the use phase of multiple wash cycles

5.14.2 Global Warming Potential

Figure 5.22 shows the cradle-to-usage global warming potential for the laundry lifetime of PLA, PET and cotton fabric. Global warming potential is the most significant environmental problem as this is linked to the use of fossil fuels and consequent greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2) emissions associated with the lifecycle of materials (De_Richter and Caillol 2011, Richardson *et al.* 2009). The GWP was evaluated based on the CML2001 impact category for 100 years, indicating the residual atmospheric time for most significant greenhouse gas, carbon dioxide equivalent.

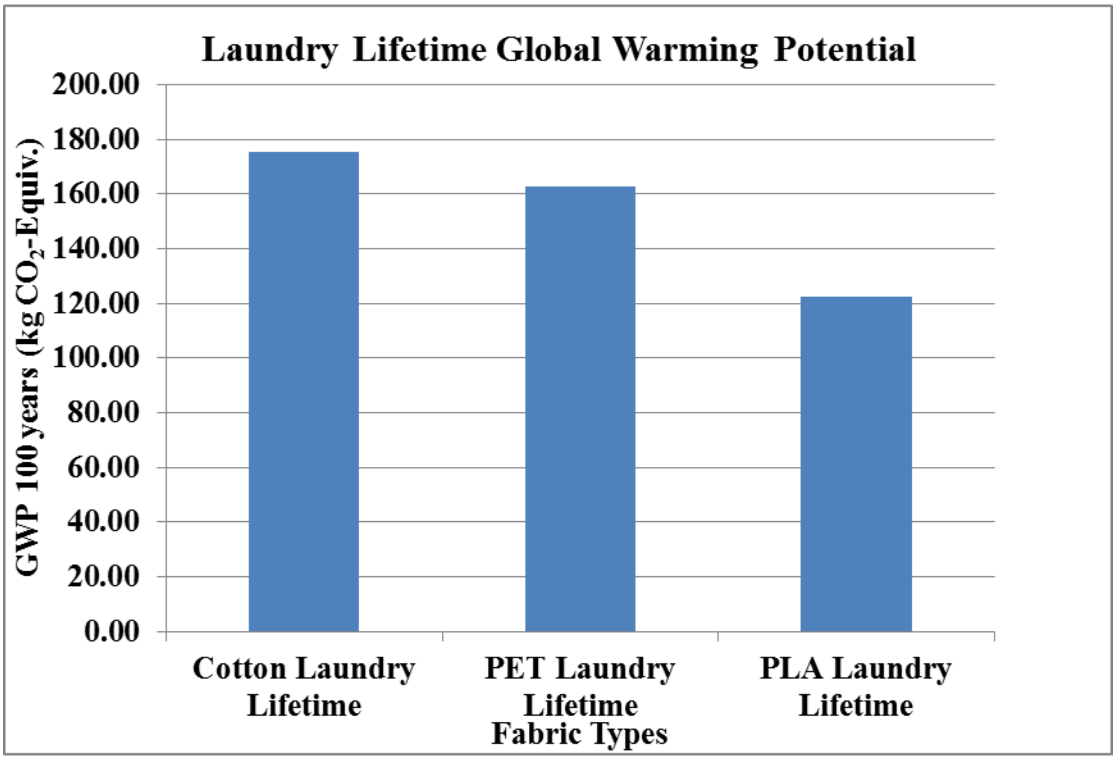

Figure 5.22: Cradle-to-usage global warming potential for 0.25kg of PLA, PET and Cotton fabric during their lifetime of 35, 42 and 43 laundry cycles respectively

The LCA shows that cotton contributed the largest 175.43 kg CO_2-Equiv. GWP compared to PET, 162.73 kg CO_2-Equiv and PLA, 122.32 kg CO_2-Equiv. This indicates that cotton t-shirt with seven laundry cycles more than PLA contributes twice as much GWP over its life cycle. Figure 5.23 show a breakdown of the global warming potential of the fabric by the different unit process.

5.14.2.1 PLA Global Warming Potential

Figure 5.23 show that about 99% of the total CO_2-eq contributed during the lifetime of PLA is from laundry use phase. This is directly related to the high amount of energy required during the laundry process, which includes energy consumed by the washing machine, tumble-drying and energy needed to heat up the water used in washing. About 95% of the GWP is associated with utilization and production of electricity consumed by the washing machine and heating of water during the use phase (Koerner *et al.* 2011). Another reason for the high CO_2-eq is because the GWP emission during corn cultivation, production of granulate and fabric manufacturing is fixed and lower than 1 kg CO_2-Equiv, while the laundry lifetime of 35 wash cycles for PLA accounted for 115.67 kg CO_2-Equiv throughout the lifetime of the fabric. The next highest GWP emission process for PLA is the production of granulates followed by corn cultivation while the fabric manufacturing was the least (Table 5.8)

Table 5.8: Greenhouse gases, methane (CH_4) and carbon dioxide (CO_2) emissions for PLA fabric during the laundry lifetime of 35 wash cycles (kg CO_2-Equiv)

PLA GWP Potential	Corn Cultivation	PLA Granulate	Fabric Manufacturing	Laundry Use Phase
Methane	0.001	0.02	0.005	6.10
Carbon dioxide	0.038	0.38	0.11	115.67
Total	0.039	0.40	0.11	121.77

5.14.2.2 PET Global Warming Potential

The largest CO_2-eq contributing process for the PET fabric is also the use phase (Figure 5.23). This contributes about 90% of the total CO_2-eq emissions during the lifetime. Similar to PLA, this is also related to the high amount of energy required during the laundry process, which includes energy consumed by the washing machine, tumble-drying and energy needed to heat up the water used in washing. The next highest GWP process for PET is the fabric production stage followed by the manufacture of granulates then fleece and crude oil extraction respectively (Table 5.9) which contributed 26% of the total GWP. The fabric production phase involves process heat and fossil energy intensive procedures to manufacture the fabrics.

Table 5.9: Greenhouse gases, methane (CH_4) and carbon dioxide (CO_2) emissions for PET fabric during the laundry lifetime of 35 wash cycles (kg CO_2-Equiv)

PET GWP Potential	Crude Oil Extraction	Granulate Production	Fleece Production	Laundry Use Phase	Fabric Manufacturing
Methane	0.119	0.270	0.029	7.35	1.61
Carbon dioxide	0.154	2.11	0.71	139.67	10.71
Total	0.273	2.38	0.74	147.02	12.33

5.14.2.3 Cotton Global Warming Potential

Similar to PLA and PET, the use phase also accounts for the major CO_2-eq contributing process for cotton during its lifetime. This accounted for 86% of the total CO_2-eq emissions which is entirely associated with the high amount of energy used during the laundry process (Figure 5.23). The next major GWP process for cotton fabric is the production of yarn and fabrics manufacturing stage, followed by the yarn production and fibre cultivation respectively (Table 5-10). Figure 5.23 illustrates the global warming potential for each unit process of PLA, PET and cotton fabrics over their lifetime.

Table 5.10: Greenhouse gases, methane (CH_4) and carbon dioxide (CO_2) emissions for cotton fabric during the laundry lifetime of 35 wash cycles (kg CO_2-Equiv)

Cotton GWP potential	Fibre Cultivation	Yarn Production	Fabric Manufacturing	Laundry Use Phase
Methane	0.04	1.31	1.61	7.53
Carbon dioxide	0.75	10.49	10.71	143
Total	0.79	11.80	12.33	150.52

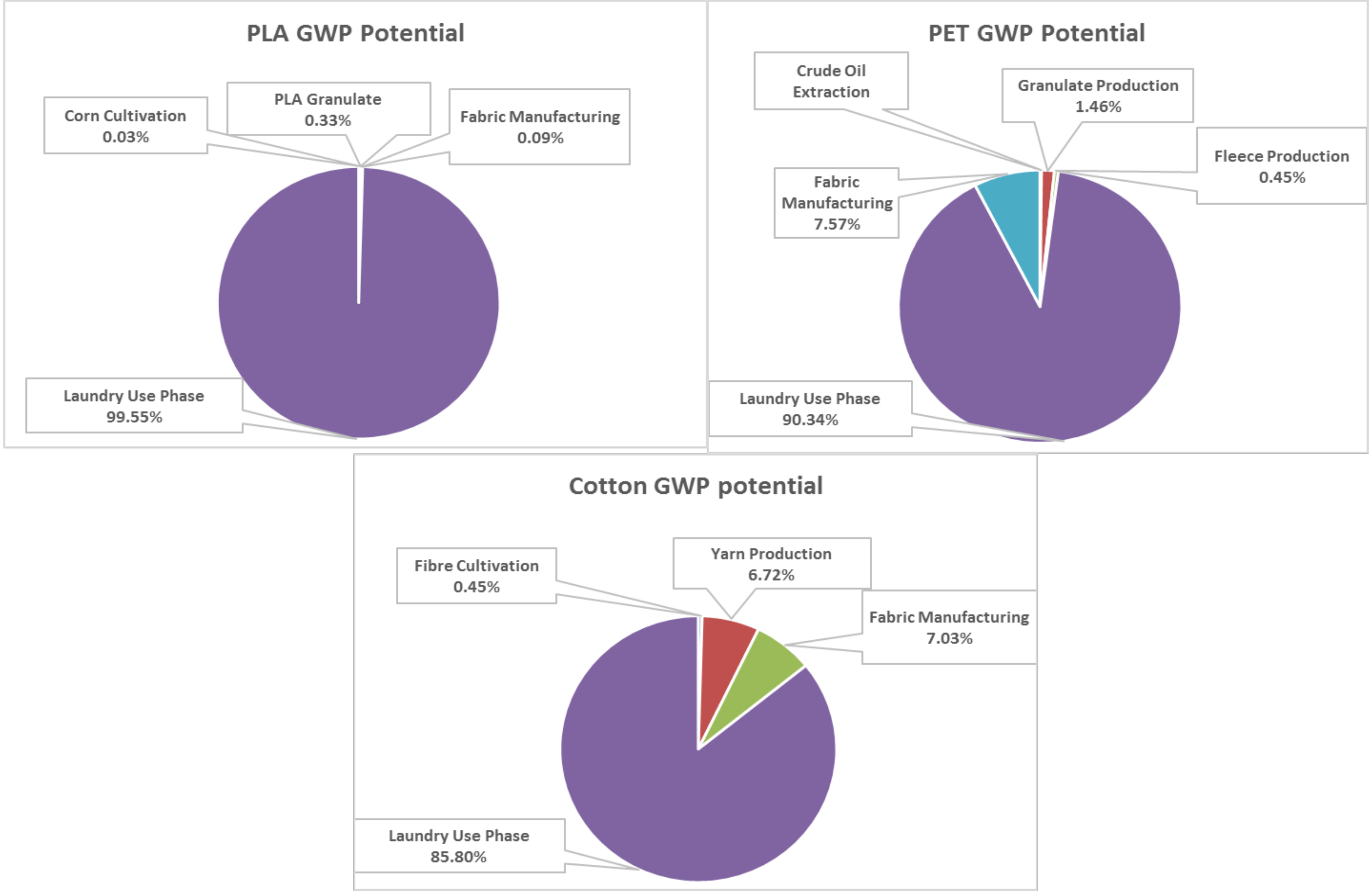

Figure 5.23: Breakdown of the global warming potential per unit process for the cradle-to-usage (laundry lifetime) of 0.25kg PLA, PET and Cotton t-shirt. The GWP for all other processes except the laundry use phase is constant. Multiple wash cycles account for the high percentage of GWP during the use phase of the laundry lifetime

5.14.3 Water Consumption

Figure 5.24 shows the cradle-to-usage water consumption for the laundry lifetime of PLA, PET and cotton fabric. The water consumption was expressed as an aggregate of water from the ground, lake, river sources, process water used for cooling, irrigation water and another natural origin such as sea water.

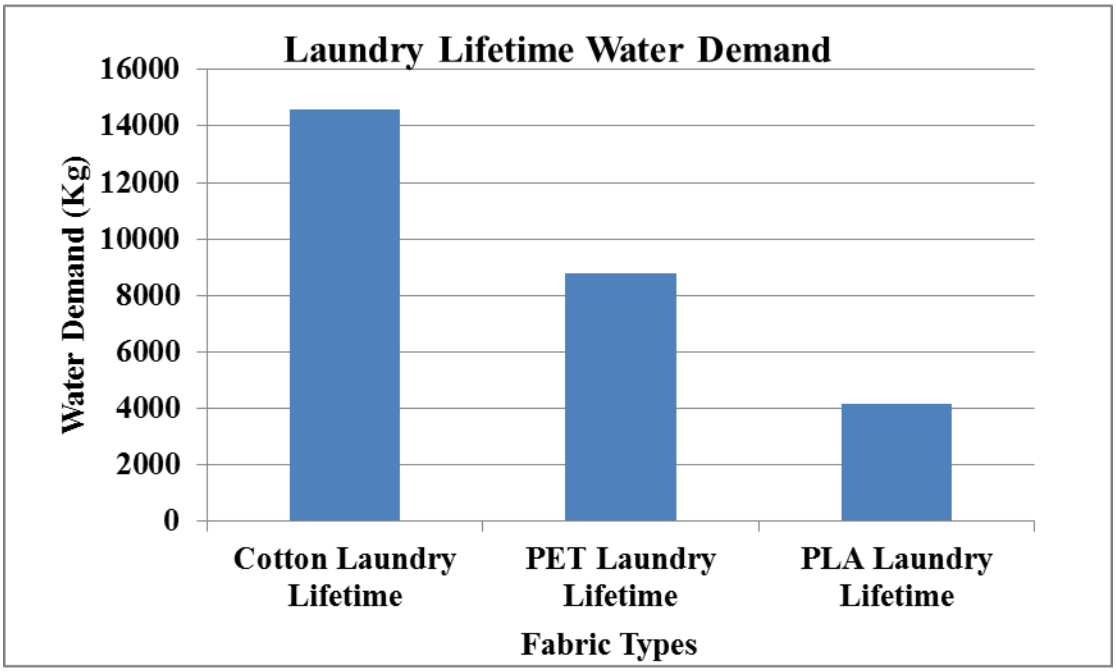

Figure 5.24: Cradle-to-usage total water consumption for 0.25kg of PLA, PET and Cotton fabric during their lifetime of 35, 42 and 43 laundry cycles respectively

The result in Figure 5.24 shows that cotton consumed the largest, about 53% of water compared to PET, 32% and PLA, 15% during their lifetime. This is equivalent to about 339kg, 209kg and 119kg per cycle for cotton-PET and PLA respectively. The results do more than suggest that from corn cultivation to its laundry lifetime PLA consumed 89kg less water than PET per cycle. This closely matches the findings of Vink *et al.*(2003), that the total amount of water PLA requires is competitive with the best-performing petrochemical polymers. A breakdown of the water consumption for each fabric and their unit process is further analysed in Figure 5.25.

5.14.3.1 PLA Water Consumption

The absolute amount of water PLA used was 4177kg during its lifetime of 35 laundry cycles (Figure 5.24). The largest water-intensive process, relating to about 98%, during the lifetime of PLA fabric, was associated with use while corn cultivation showed the least intensive process (Table 5.11). This is directly linked to the number of laundry cycles during its lifetime. The next water-intensive process related to fabric manufacturing (29kg of water), this is associated with the operational water consumption during the production of electricity used for process and weaving the fabric. Table 5.11 shows the water consumption by unit process for PLA fabric. As shown in Figure 5.25, the other process, production of lactide and granulate, and cultivation of corn consumed a relatively little amount of water compared to the use phase.

Table 5.11: Water consumption (kg) by unit process during 35 laundry cycles for PLA fabric

Unit Process	Corn Cultivation	PLA Granulate	PLA Fabric Manufacturing	Laundry Use Phase
PLA Water resources (kg)	9.479	7.84	29.28	4130

5.14.3.2 PET Water Consumption

The absolute amount of water PET used was 8779kg during its lifetime of 42 laundry cycles (Figure 5.24). The major water consuming process, relating to about 94%, for PET, was also the use phase while the crude oil extraction was the least consuming process (Table 5.12). Similar to PLA, this is directly linked to the number of laundry cycles during its lifetime. The next intensive process for PET is the fabric manufacturing, relating to about 4.5% of the total water consumption, is associated with the operational water consumption during the production of electricity used in the production phase. The bulk of water utilised in both processes relates to process and cooling water used in washing, and to prevent overheating of the equipment. Table 5.12 shows the water consumption by unit process for PET fabric. The other processes, such as the production of PET granulates (0.97%), production of fleece (0.4%) and extraction of crude oil (0.008%) were not as water intensive as the use phase (Figure 5.25).

Table 5.12: Water consumption (kg) by unit process during 42 laundry cycles for PET fabric

Unit Process	Crude Oil Extraction	Granulate Production	Fleece Production	Fabric Manufacturing	Laundry Use Phase
PET Water resources	0.1679	85.37	34.95	400.10	8259

5.14.3.3 Cotton Water Consumption

The absolute amount of water cotton used was 14,594kg during its lifetime of 43 laundry cycles (Figure 5.24). Similar to the other materials, the use phase also accounts for the largest water-consuming process in the lifetime of cotton. However, this stage only consumed about 58% of the total water demand compared to the >90% of PLA and PET. The next water-intensive process for cotton is the yarn production relating to about 35% of the total water consumption This agrees with the result of Shen and Patel (2010) who found that during fabric production, the use of cooling water accounted for 90-95% of the total water consumed excluding the use phase. This is attributed to the high energy demand during the fibre processing, and wet preparation of fabric manufacturing phase, which in turn requires a significant amount of water to keep the machines cool. The other processes, such as cotton fibre production (4%) and fabric manufacturing (3%) were not as water intensive as the use phase (Figure 5.25).

Table 5.13: Water consumption (kg) by unit process during 43 laundry cycles for cotton fabric

Unit Process	Cotton Fibre Cultivation	Cotton Yarn Production	Cotton Fabric Manufacturing	Cotton Use Phase
Cotton Water Demand	680	5059	400	8456

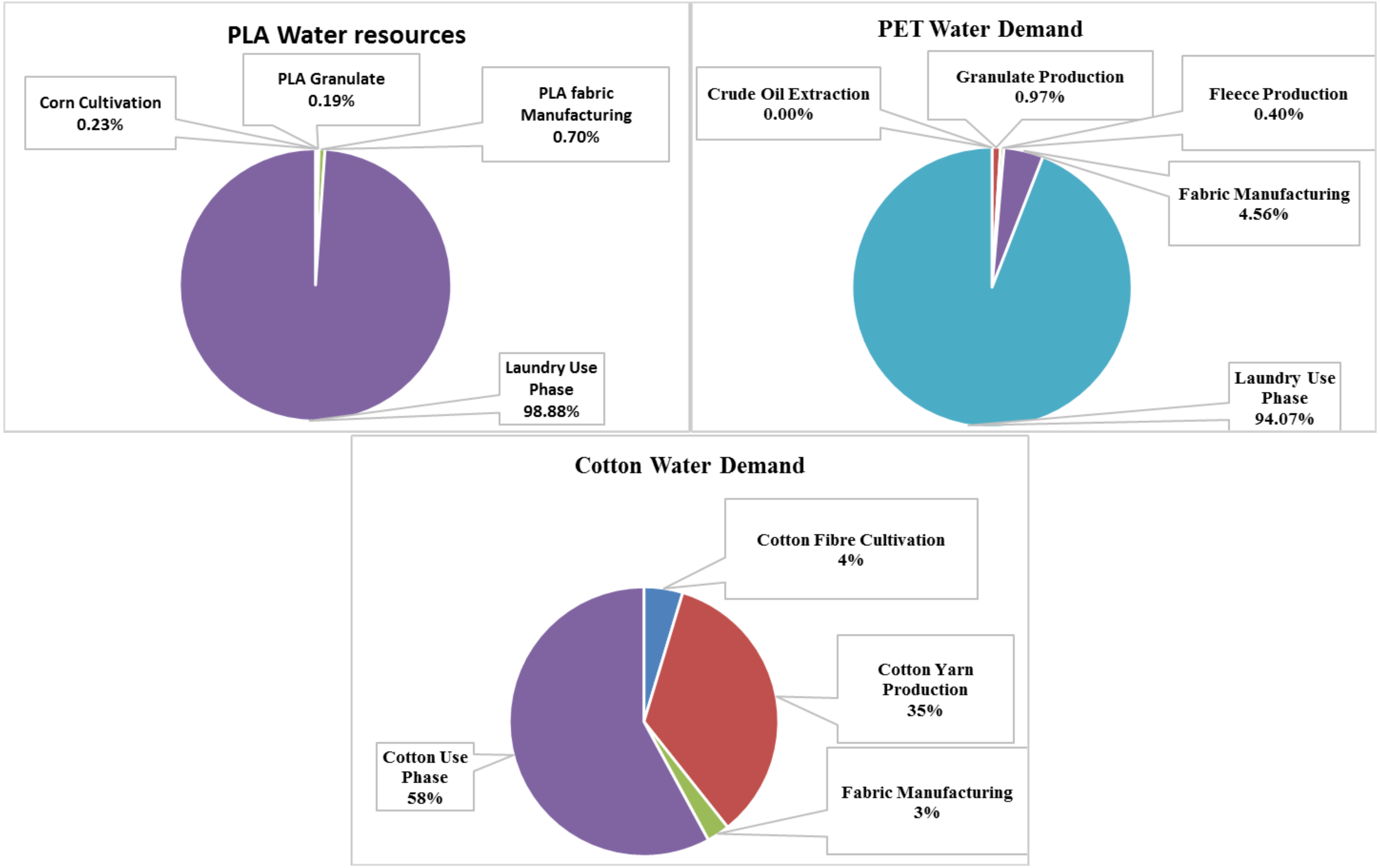

Figure 5.25: Breakdown of the water consumption per unit process for the cradle-to-usage (laundry lifetime) of 0.25kg PLA, PET and Cotton t-shirt

5.15 Life Cycle Impact Assessment for School t-shirt made from PLA, PET and Cotton

This section of the study takes into account the end use, for example a school t-shirt made from PLA, PET and cotton used for a year. The aim is to assess the impact differences between the experimental lifetime when the durability is enhanced to last at least 75 wash cycles for a school t-shirt.

5.15.1 Functional Unit

A school t-shirt is washed up to 75 times during an academic year (section 5.4.1). Using equation 6, and the lifetime laundry cycle for the fabrics (Table 5-4), the functional unit for a school t-shirt produced to wash 75 times per year was calculated as shown in Table 5.14

Table 5.14: Functional Unit for the enhanced durable school t-shirt made from PLA, PET and Cotton

Fabric	Functional Unit for 75 wash cycles
PLA	0.54
PET	0.45
Cotton	0.44

5.15.2 Cumulative Energy Demand

Figure 5.26 shows the cradle-to-usage cumulative energy demand for the laundry lifetime of a school t-shirt made from PLA, PET and cotton fabric. The results of the assessment showed that the energy demand ranges between 3500 MJ- 4000 MJ for all the fabrics. The slight difference in the energy demand between PLA, PET and cotton school t-shirt could be due to the same number of wash cycles. A breakdown of the energy requirement per unit process for each fabric life cycle was similar to the experimental laundry lifetime illustrated in Figure 5.21.

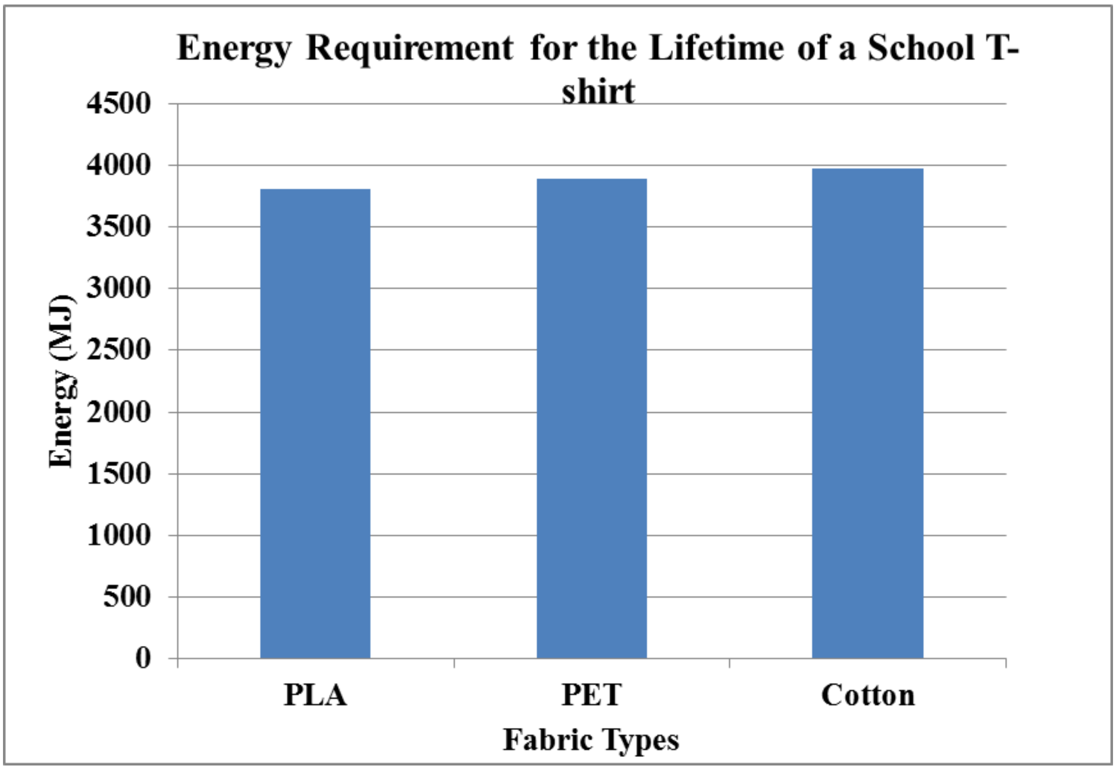

Figure 5.26: Energy requirement from cradle to 75 laundry cycles per year for a school t-shirt made from PLA, PET and cotton

5.15.3 Global Warming Potential

Figure 5.27 shows the cradle-to-usage global warming potential for the laundry lifetime of a school t-shirt made from PLA, PET and cotton fabric. The result of the LCA shows that cotton uniform contributed the largest 41% GWP compared to 34% by PET and 24% by PLA. A breakdown of the energy requirement per unit process for each fabric life cycle was similar to the experimental laundry lifetime illustrated in Figure 5.23.

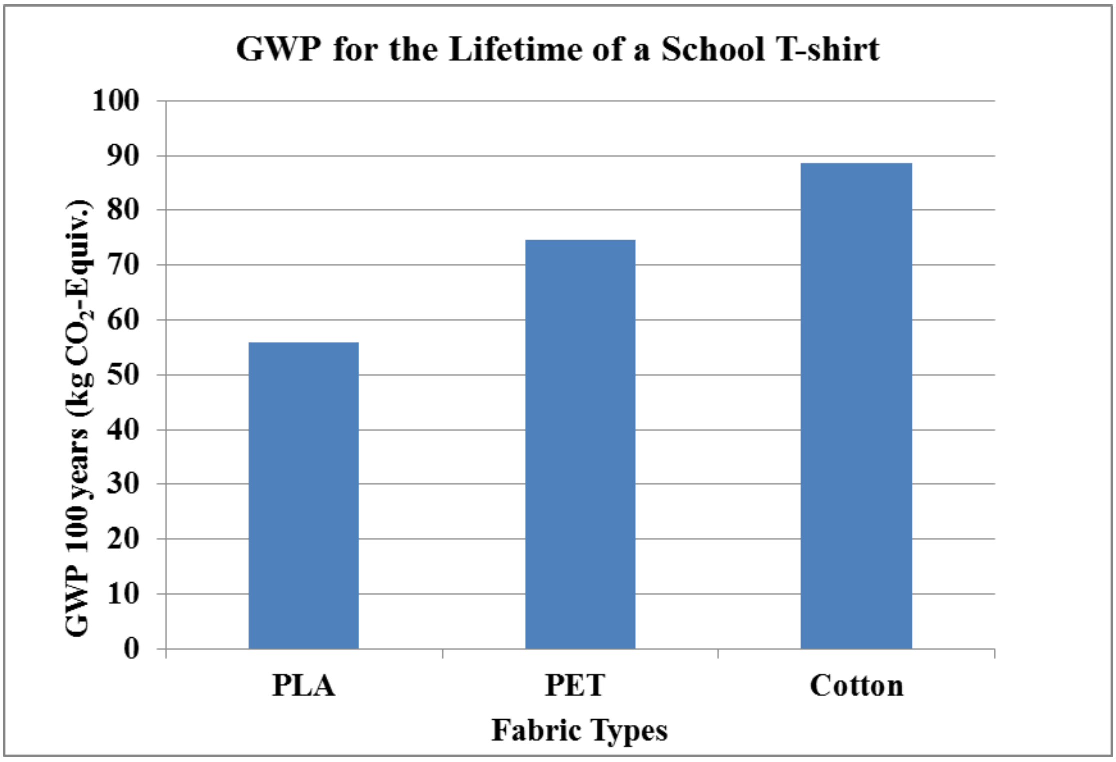

Figure 5.27: Global warming potential from cradle to 75 laundry cycles per year for a school t-shirt made from PLA, PET and cotton

5.15.4 Water Consumption

Figure 5.28 shows the cradle-to-usage global warming potential for the laundry lifetime of a school t-shirt made from PLA, PET and cotton fabric. The LCA result shows that cotton consumed about 50% of the total water demand water compared to PET, 25% and PLA, 24% during the lifetime of a school t-shirt. A breakdown of the energy requirement per unit process for each fabric life cycle was similar to the experimental laundry lifetime illustrated in Figure 5.25

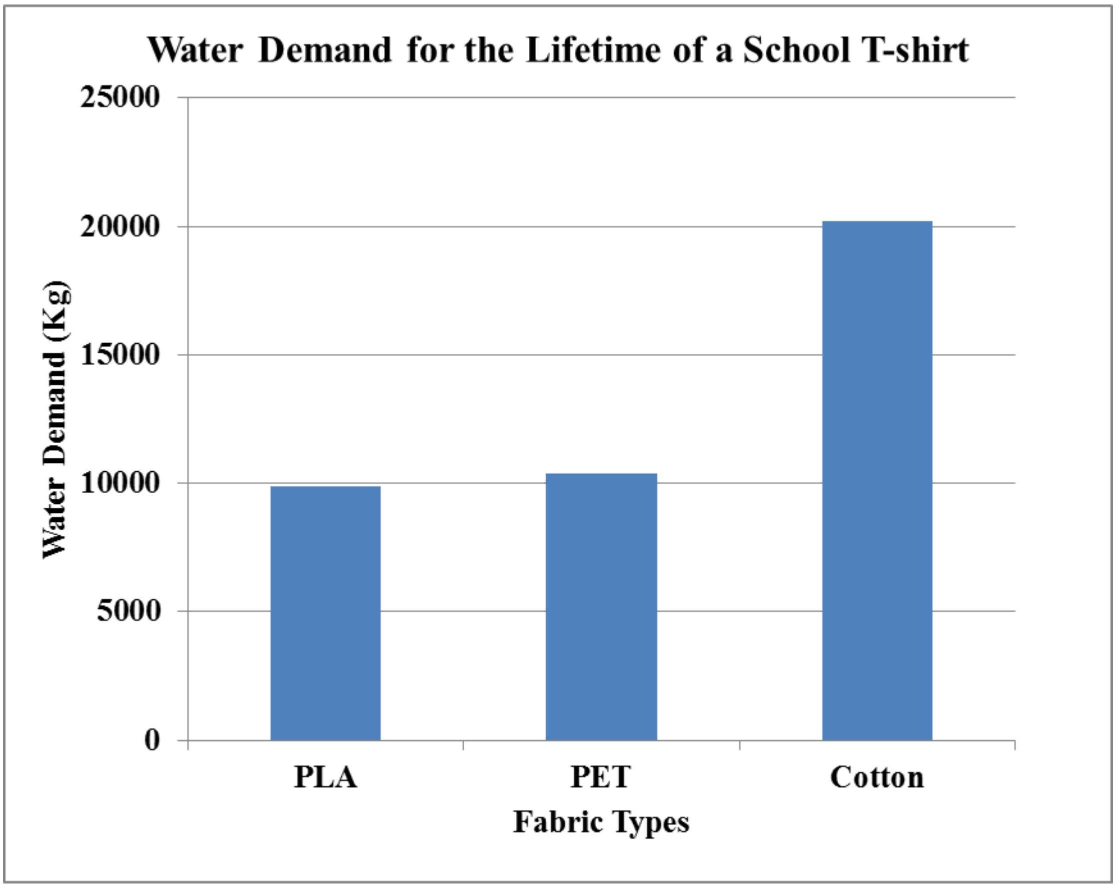

Figure 5.28: Water consumption from cradle to 75 laundry cycles per year for a school t-shirt made from PLA, PET and cotton

5.16 Comparative impact of the Laundry and School t-shirt Lifetime

This section compares the life cycle impact assessment of the laundry lifetime and the school t-shirt lifetime. The result is reported as a proportion of the total impact on the three fabrics in Figures 5.29 to Figure 5.31.

5.16.1 Cumulative Energy Demand

The proportion of total energy demand in percentage for PLA, PET and cotton fabric during their laundry and the school t-shirt lifetime used for the whole year is compared in Figure 5.29. The LCA result shows that when the laundry lifetime was increased, the energy demand for PET and cotton as a proportion of the total energy of the three fabrics for the school t-shirt decreased by 5-6% compared to the laundry lifetime. On the contrary, the energy demand for PLA as a proportion of the total energy of the three fabrics for the school t-shirt increased by 11% compared to the laundry lifetime. Also the percentage energy demand for all three fabrics ranged between 33-34% (Figure 5.29b), when the lifetime of all fabrics were increased to last for 75 laundry cycles per year. This result suggests that increasing the lifetime of PLA fabric does not improve its energy demand. Rather it increases the overall energy demand for PLA making it comparable to PET and cotton of the same end use. The reason for this is not quite clear.

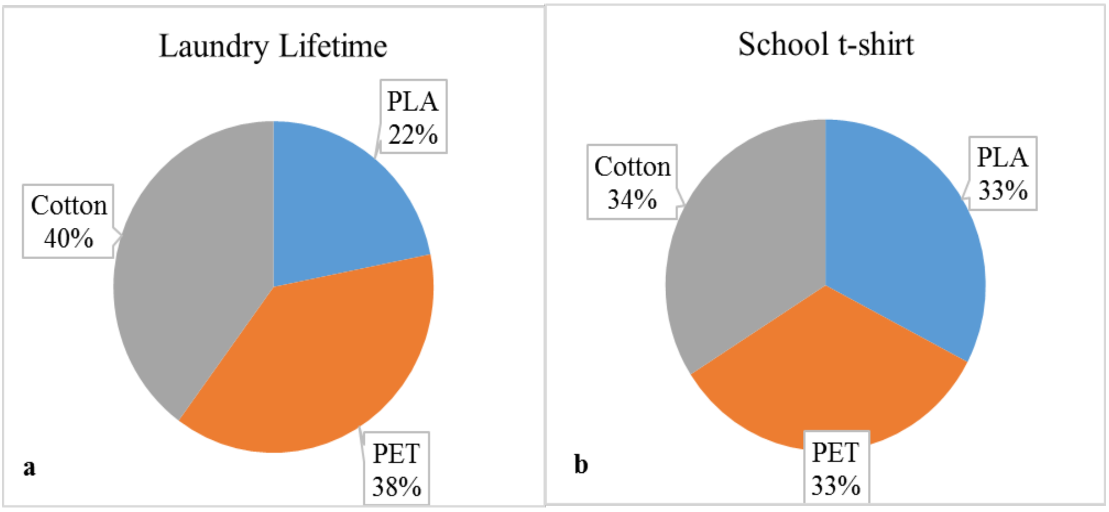

Figure 5.29: Total energy demand in percentage for PLA, PET and cotton fabric during their (a) laundry and the (b) school t-shirt lifetime

5.16.2 Global Warming Potential

The proportion of global warming potential in percentage of PLA, PET and cotton fabric during their laundry and the school t-shirt lifetime used for the whole year are compared in Figure 5.30. The LCA results show that when the laundry lifetime was increased, the GWP for PET and cotton as a proportion of the total GWP of the three fabrics for the school t-shirt decreased by 1-3% compared to the laundry lifetime. On the contrary, the GWP for PLA increased from 22% for the laundry lifetime to 26% for the school t-shirt laundry lifetime. This result suggests that increasing the lifetime of PLA fabric does not improve its GWP. Rather it increases the overall GWP for PLA compared to PET and cotton of the same end use. Further research will be required to understand the reason for this increase in the GWP for PLA fully. However, the result suggests that increasing the lifetime of PLA fabric does not improve its overall GWP.

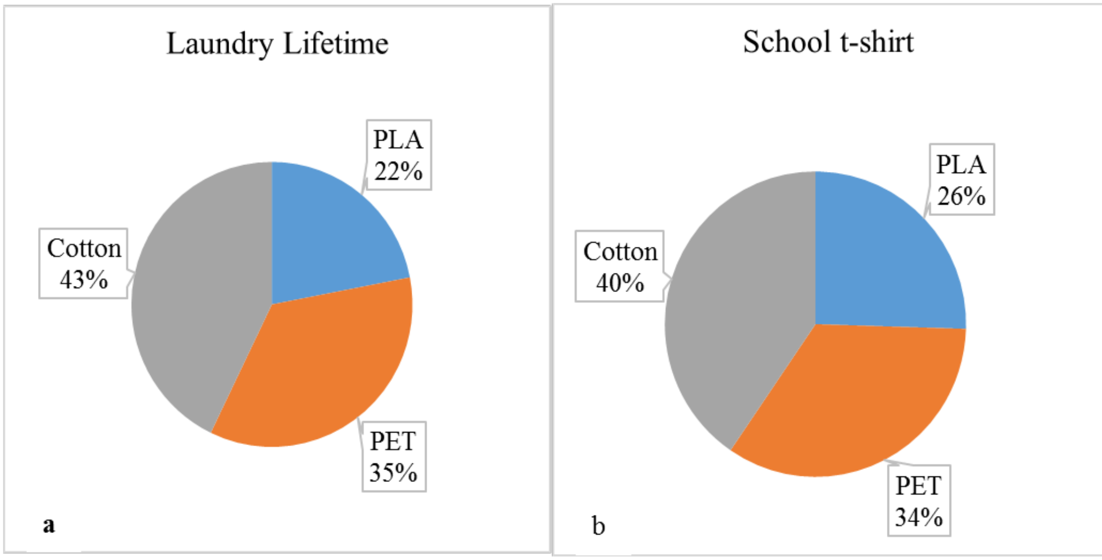

Figure 5.30: Total global warming potential percentage for PLA, PET and cotton fabric during their (a) laundry and the (b) school t-shirt lifetime

5.16.3 Water Consumption

The proportion of water consumption in percentage of PLA, PET and cotton fabric during their laundry and the school t-shirt lifetime used for the whole year is compared in Figure 5.31. The LCA results show that when the laundry lifetime was increased, the water consumption as a proportion of the water demand of the three fabrics for PET remained the same while cotton decreased by 3% for the school t-shirt compared to the laundry lifetime. On the other hand, the water demand for PLA increased from 21% for the laundry lifetime to 24% when the lifetime was increased to the school t-shirt laundry lifetime. This result suggests that increasing the lifetime of a PLA fabric does not improve its water demand. Rather it increases the water consumption for PLA compared to PET and cotton of the same end use. Further research will be required to understand the reason for this increase in the water demand for PLA fully.

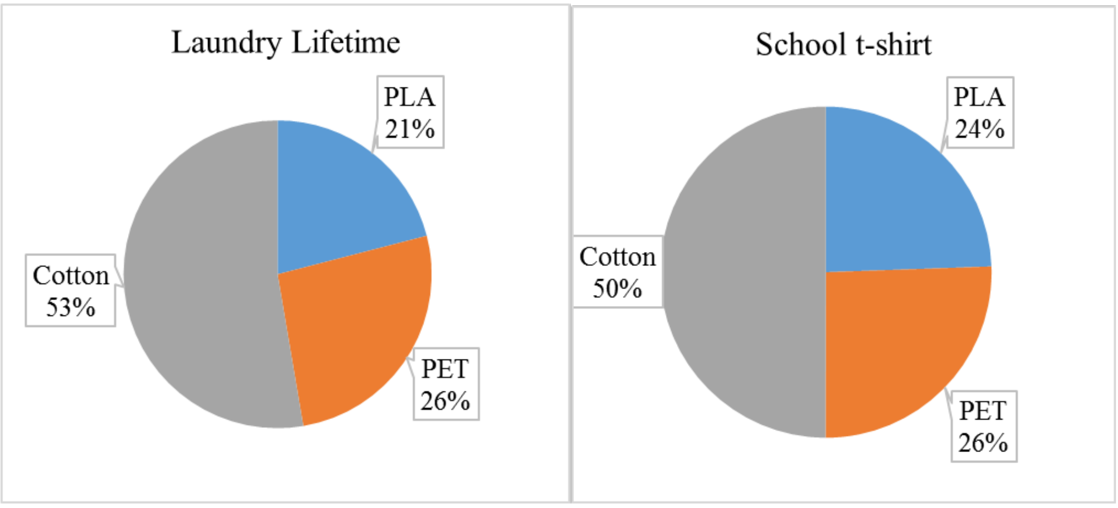

Figure 5.31: Total water demand in percentage for PLA, PET and cotton fabric during their (a) laundry and the (b) school t-shirt lifetime

5.17 Summary

This section of the study examined the life cycle assessment of PLA, PET and cotton fabric and the potential of adopting PLA as an alternative fabric to cotton and PET. The goal and scope of the study was to assess the associated environmental impact within the cradle to the laundry use phase of the fabrics. Emphasis was laid on the use phase where the bulk of the environmental impact is assumed to be prominent. The functional units used in this study were defined as the production and laundry of a 0.25kg t-shirt and number of wash per year using a school t-shirt washed for 75 times per year as a reference.

The laundry cycle that best describes the life expectancy of the fabric was evaluated by introducing a durability and lifetime indicator using the results from the tensile strength, extension and tensile modulus. This calculation was based on the assumption that the lifetime of the fabrics is proportional to the tensile properties and number of laundry cycles. It was revealed that the lifetime indicator which was expressed in number of laundry cycles were 35, 42 and 43 wash cycles for PLA, PET and cotton respectively.

Incorporating this into the life cycle assessment reveal the 0.25kg t-shirt made from PLA demanded less energy, water and emitted the lowest CO_2-eq compared to PET or cotton due to the short laundry lifetime. For all three impact categories measured, the use phase was identified as the most energy intensive, water demanding and largest global warming contributor of the fabric's life cycle. The result also revealed that the environmental impact of cotton decreased by 2%, PET decreased by about 1.2%, while PLA increased by 3% when the laundry lifetime was increased to 75 wash cycles.

6 DISCUSSION

This chapter reflects on the main findings of the research regarding its contributions to whether PLA can offer fabric with lower environmental impacts over a period of its lifetime and through several washing cycles compared to PET and cotton. The research also sought to answer the question on what environmental impact PLA fabric incur will when the life expectancy was extended up to 75 wash cycles compared to PET or cotton.

Section 6.1 and 6.2 considers the influence of laundry on the deformation behaviour of the fabrics during the pilot and the main test. Section 6.2 also compares the influence of different laundry treatments (DT, DA, DST and DSA) and the number of laundry cycles on the deformation behaviour of PLA, PET and cotton fabric. The environmental impact of the fabric during their life expectancy is compared in section 6.3 based on the number of laundry cycles that each fabric can withstand before any significant effect is noticed in the behaviour or mechanical properties. Section 6.4 reflects on the environmental impact of the fabric when the life expectancy was increased to 75 wash cycles of a school t-shirt. This section also compares the impact of the experimental laundry lifetime and the school. Finally Section 6.5 provides some limitations to the study.

6.1 Influence of laundry on deformation behaviour of the fabrics: pilot experiment

Before the main study, a pilot experiment was conducted to investigate and compare the influence of laundry and tumble-drying on PLA, PET and cotton fabric. For the unwashed fabrics, the results of the tensile test showed differences in the tensile properties of PLA, PET and cotton fabric due to their chemical constituents and the physical brittleness of the fabrics. As expected, chemical deterioration takes place in the constituent fabrics in reaction to water and laundry detergent, and low-stress mechanical agitation in the washing machine translate to a loss of the tensile properties with progressive washes. In general, PLA fabric retained its load-extension profile up to 10 laundry cycles, irrespective of the laundry treatment after which hydrolysis of the polymer bonds within the fibre due to laundry and tumble-drying caused mechanical damages and loss in tensile properties from laundry cycle 30 onward. PET fabric, on the other hand, seemed to retain its load-extension profile and behaviour throughout the laundry cycle irrespective of the laundry treatment. However, cotton fabric continued to show progressive damages during the laundry cycles.

In comparison, the load-extension profiles from the pilot experiment and the actual research experiment show a similar trend considering the modification of the experimental parameters (from 10mm/min to 100mm/mm), 50k N load cell. The behaviour of the unwashed fabrics shows a higher load at yield for cotton fabric compared to PLA fabric, which showed a higher yield load with the lower extension than PET with a lower yield load and greater extension. Compared to the behaviour of the unwashed fabric, one laundry and tumble dried cycle showed a 14% decrease in the yield load and a 12% increase in the extension of cotton fabric. While PET showed a 17% decrease in yield load at 19% less extension than the unwashed fabric.

In the analysis of the influence of laundry regime (one, three, six, 10, 30 and 50 washes) on PLA, PET and cotton, changes in the shape of the load-extension curve, extension of the fabrics at the initial inter-yarn rearrangement and the variance of the yield load for each fabric after each laundry regime were characterised. After each laundry cycle, the early stages of extension before linear elasticity were less than 5mm for PLA while

PET showed an extension of 5mm approximately for all laundry conditions. However, cotton showed a range of extensions for tumble-dried fabrics, with or without softeners. On the other hand, the initial stages of extension before linear elasticity for air-dried cotton fabrics were not significantly different with or without softeners. It is assumed that there were no significant changes in the crystallinity of PLA and PET fabric during the laundry regime with or without tumble-drying or fabric softener. PET fabric showed similar yield point at extensions between 11-15 mm, indicating a consistency in the behaviour of PET after each laundry cycle and the different conditions. This is because moisture absorption during laundry is very small, and the recurring benzene ring of PET fabrics aids hydrophobicity and low water absorption (Fashola *et al.* 2012).

6.2 Influence of laundry treatments on tensile behaviour and properties of the fabrics: main experiment

The influence of different laundry treatments (DT, DA, DST and DSA) and number of laundry cycles on the deformation behaviour of PLA, PET and cotton fabric show that changes in the tensile behaviour rely heavily on fabric type. PLA fabric shows some behaviours and properties which are comparable to PET and cotton fabric. For instance, the shape of load-extension curve, which is divided into three regions, is similar for PLA and PET. This is analogous to the three-zone load-extension curve for PLA reported in Zupin and Dimitrovski (2010). Although cotton fabric exhibited a concave load-extension curve, which is different from PLA, both fabrics still share similarities in tensile properties such as the load at break and their response to repeated laundry regimes. The result showed an initial non-linear portion of the three stages exhibited by both PLA and PET fabrics, arising from the bending resistance of constituents adjacent yarns as they straighten and rearrange under a small 1 N load and 1.5mm extension.

Though the PLA and PET fabric show similar load-extension profiles, the results of the effect of different laundry conditions were disparate. In fact, there seem to be more similarities between cotton and PLA fabric in tensile properties because both fabrics are made from natural renewable materials (Zupin and Dimitrovski 2010). Therefore, their behaviour during the laundry regime has similar characteristics. In comparison to PET, the tensile properties of PLA seems to decline more in response to the laundry regime both fabrics were subjected to. This could be due to the poor alkali resistance of PLA leading to a loss in tensile properties via hydrolysis (Avinc and Khoddami 2010, Avinc 2011), as a result of the multiple exposures to the alkali medium generated from the laundry detergent.

The results of the pilot and main research experiment on tensile properties of PLA fabric with increasing laundry cycle are similar to those of Idumah *et al.* (2013) who reported that PLA exhibited a consistent rise in the tensile extension when subjected to a wet or heat setting application. Another reason for this increase in extension could be the structure of the weave. For PLA, though the extensions at yield point were between 9-15mm, the yield load for all laundry cycles of the air-dried fabrics with or without softener was not significantly different. The tumble-dried fabric seems to show a significant difference between the laundry regime regardless of the use of softener. In fact, after laundry cycles 10, 30 and 50, tumble-drying appears to have a significant influence on the shape of the load-extension curve. Although the linear elastic region appears to have similar slope, the yield points are far lower than cycles one to six. The fabric used for this study were plain weave, which has high interlacing of yarns and crimp in the adjacent yarns' direction, consequently an increase in the yarn crimp leads to a rise in the fabric extension in any direction (Adanur 2002). Fibre swelling could also result in increased fabric extension. For PET fabric, a gradual increase in the tensile extension is observed to increase during the first few laundry cycles due to the swelling, leading to yarn crimping. Fibre swelling during the wash creates a tight and relaxed condition between the fabric fibres thereby causing the fabric to resist extension. Hence, there are small changes in the extension of subsequent wash cycles. Due to the hydrophobic and crystalline nature and the toughness of PET fibres, significant swelling does not occur in water; thereby little resistance occurs allowing for extra extension.

As expected with the cotton fabric there were no significant changes in the tensile extension after 50 wash cycles compared to the unwashed fabric because cotton is made up of rigid cellulose fibre chains with a large portion of the molecules constrained to a crystalline lattice. Consequently, there is no room for any internal chain mobility with this type of structure (Wakelyn *et al.* 2006). In addition, cotton fabric shows similarities in its tensile properties for the breaking load, percentage extension at break, modulus and the tensile strength. This closely matches the results in Avinc and Khoddami (2010) which showed that there is a close similarity in some tensile properties of cotton and PLA. For cotton fabric, the extension at yield/breaking point was between 26-32 mm and 22-38 mm for DA/DSA and DT/DST respectively. Although the influence was greater with the addition of fabric softener for the tumble-dried fabrics, the behaviour of cotton after each laundry cycle was not consistent. This is because cotton fibres are absorbent and tend to swell about 40% during laundry (Bishop 1995, Üreyen *et al.* 2012) more than PET and PLA. In the wet state, swelling produces bottleneck between the adjacent yarns of cotton fabric that they cannot move freely. However, according to Bishop (1995) the final properties of cotton depend on the nature of the drying process.

In contrast to PLA and PET, cotton fabric absorbs more water, which influences an increase in the thickness, weight and possibly thread count of the fabric. This in turn has an effect on the breaking strength of cotton fabric (Malik *et al.* 2010). In the PLA fabric, there was no change in tensile elongation in both directions after one and three laundry cycles, in comparison to the unwashed fabric. Because there were no alterations in the yarn spacing during the first few wash cycles, the crimp value remains the same (Banerjee *et al.* 2010) in the warp direction of the PLA fabric subjected to three laundry cycles.

Tensile modulus for PLA, PET and cotton have been analysed and described in Appendix 1. As shown in Section 4.5.1.12 the higher the tensile modulus, the stiffer the fabric and the firmer and more resistant to stretching the fabric will be. Fabric washed in DT shows a higher and increasing tensile modulus when compared to fabrics washed in DA while fabrics washed in DST and DSA seem to retain their tensile modulus up to 30 laundry cycles. The 6-10% increase in the tensile modulus of PLA after tumble-drying (section 4.5.1.1) closely match the result of Karst *et al.* (2009) who found that tumble-dried PLA at 50ºC or 70ºC retains its tensile modulus.

The reason for low and decreasing tensile modulus of the DA could be attributed to hydrolysis. This is a reaction where high molecular weight polyester chains depolymerizes to produce shorter and lower molecular chains (oligomers) with alcohol (-OH) and carboxylic (-COOH) groups as a result of water molecules splitting into hydrogen and hydroxide ions in the process of a chemical mechanism (Avinc *et al.*

2010, Miller *et al.* 2009). Although there is no mechanical agitation during air-drying, the longer PLA fabric stays moist, the higher the rate of hydrolysis, which in turn reduces the tensile modulus of PLA fabric. On the other hand, during tumble-drying (DT), because PLA is dried more quickly, the mechanical agitation is bound to affect the physical surface of the fabric. The consistency and the retention of tensile modulus for fabrics washed in DSA or DST closely match the assumption of Avinc *et al* (2010) that softener application does not have any adverse effect on the tensile properties of PLA. A possible reason for this is that the hydrophobic properties of softeners increase the water repellency on the fabric as well as reducing any inter-fibre friction (Khoddami *et al.* 2010).

With increasing laundry cycles, a general increase in the tensile modulus of PET fabric was observed, and this increase is further enhanced with the use of fabric softener. The maximum increase in tensile modulus was observed after laundry cycle 1 of DT, after which it reduced and stabilised until laundry cycle 50. The reason for the increase in tensile modulus is the relaxation state of PET fabric, which seems to increase as the laundry cycle increases. The cylindrical shape of the fibres causes the yarn to tighten and enhances the friction between the yarns. After laundry cycle one, the influence of the laundry treatment showed a 17% increase in the tensile modulus for DT which was greater compared to the steady 4-6% increase for DST treatments. On the other hand the DA and DSA showed similar 11 MPa tensile modulus.

The influence of different laundry treatment on cotton fabric resulted in a general decrease in tensile modulus with increasing laundry cycles. The result of DT treatment showed that there was no difference in the tensile modulus between the unwashed fabric and laundry cycle one, however with increasing laundry cycles, the tensile modulus declined steadily until laundry cycle 10 and remained consistent up to laundry cycle 50. In contrast, there was a similar, but gradual, substantial decrease of 37-47% in the tensile modulus of cotton in the DA and DSA laundry treatment with increasing laundry cycles.

From the result of the analysis in Appendix 2 (Section 4.5.1.1 – 4.5.1.3), the influence of different laundry treatments on the tensile modulus, show that the mean tensile modulus was significantly different ($p<0.001$) among the laundry treatments for PLA, PET and cotton fabric. Also, the effect of the laundry regime on the tensile modulus was found to be significant ($p<0.001$) for PLA, PET and cotton. The results also indicate that the higher the tensile modulus, the greater influence of the laundry treatment. This was found to be higher in PLA followed by cotton and then PET, however the influence of laundry regime was much higher in cotton fabric than PLA and PET. Statistical analysis showed that the load at yield was statistically different ($p<0.001$), among the laundry treatments for PLA, PET and cotton.

In general, the effect of DT treatment resulted in a greater and similar effect on PLA and cotton compared to PET fabric. DA treatment showed no significant effect on the tensile strength of PET compared to PLA and cotton respectively. The effect of DSA was found to be quite similar in PLA and cotton and insignificant compared to PET fabric. Finally, DST treatment resulted in a greater effect on cotton fabric compared to PET which showed a greater effect than PLA. The use of softener treatment may have produced a lubricating effect that increases the fibre and yarn mobility within the fabrics.

During air-drying, the fabrics are static; water tends to drain or evaporate, producing an increase in the capillarity attraction between yarns. The dried fabric retains the wet yarn formation with a strong inter- and intra-fibre adhesion formed from the hydrogen bonds of the cellulose. This was confirmed by the small changes in the shape of the load-extension curves of cotton fabric across the laundry cycles. However, during tumble-drying, the capillarity attraction between yarns reduces as the fabric shrinks due to rapid drying and constant mechanical agitation of the tumble-dryer. As a result, movement of adjacent yarns increases, preventing the formation of intra-fibre hydrogen bonds until the fabric is dried. The effect is evident by the decreasing slope and the cumulative interval between the linear elastic regions of the tumble-dried cotton fabric.

In general, the influence on the behaviour of cotton observed during 50 laundry cycles, between the tumble-dried and air-dried, with or without softener is extensive compared to PLA and PET fabrics. However, in comparison to PET, the tumble-dried PLA fabrics showed evidence of extensive laundry regime. This is because PLA has a significantly lower glass transition temperature (55 ^{o}C-60 ^{o}C) than PET (77 ^{o}C) and suggests a softer fabric that is prone to mechanical damage during laundry and tumble-drying. Arguably, similar to cotton fabric, the type of drying process also determines the performance of PLA after any laundry regime.

6.3 Environmental Impact comparison between PLA, PET and Cotton fabric during their lifetime

The lifetime environmental impact of the fabrics was assessed based on the number of laundry cycles that the fabrics can withstand before any significant effect is noticed in the behaviour or mechanical properties. Using a pairwise comparison analysis, the laundry cycle that showed a significant difference compared to the unwashed fabric was determined (see Table 5.3). PET showed a better tolerance to the laundry regime compared to PLA and cotton. The tensile modulus, tensile strength and percentage extension of PET fabric endured further laundry cycles than PLA and cotton. Based on the assumption that the lifetime of the fabric is proportional to the tensile properties and the number of laundry cycles, the lifetime indicator and number of wash cycles was calculated during their life cycle (see Table 5.4). The result indicated that PLA fabric will only wash for 35 times, which is 6-7 times less than PET or cotton during its lifetime.

As shown in Figures 5.20, 5.22 and 5.24, a 0.25kg t-shirt made from PLA demanded less energy, water and emitted the lowest CO_2-eq compared to PET or cotton. The reason for this could be that PLA had the lowest number of laundry cycles (35) during its lifetime compared to PET (42) or cotton (43). For all three impact categories measured, the use phase was identified as the most energy intensive, water demanding and largest global warming contributor of the fabric's life cycle. This result is consistent with the findings of Laursen *et al.*(2007), who carried out a cradle to grave LCA on a t-shirt, a jogging suit, a work jacket and a blouse and found that the largest resource and energy consumption came from the use phase that consist of washing and tumble-drying. During the use phase, the majority of the energy is usually consumed by the washing machine and heating of water for laundry (Cartwright *et al.* 2011, Koerner *et al.* 2011, McCoy 2011)

It is clear from Figures 5.21, 5.23 and 5.25 that the use phase for PLA fabric dominates the major part of life cycle impact. For example, 98% of the GWP, 99% of the energy and water consumption was during the laundry use phase of the PLA fabric. This suggests that the environmental impact of the cultivation of corn to the production of the fabric is insignificant compared to the use phase. However, when compared to cotton, 47% of the water consumption was used during the use phase while about 49% was consumed during the cultivation and production of cotton yarn. The impact is particularly significant because cotton consumption is responsible for about 2.6% of the global water use (Chapagain *et al.* 2006). On the other hand, when compared with PET, the use phase also consumed over 90% of the total water demand, 89% energy and contributed 67% of the GWP. This matches the results of Cartwright *et al.* (2011) and Windler *et al.* (2013) who found that the greater part of resources used and emission occurs during the use phase of fabrics. Heating of water during laundry has been attributed to 75% of the total energy consumed (Pakula and Stamminger 2010).

During the cultivation of cotton, the only recorded GWP release was in the form of CO_2 from the use of water; these are believed to be sequestrated during the agricultural production. From the result of the global warming potential of cotton fabric, the largest impact is associated with the use phase, which consists of the washing and drying of the fabric. Because cotton fabrics absorb more water than PLA and PET and therefore will require more energy to dry, this also contributes to the global warming potential. Also the high energy demand associated with the production of yarn and fabric manufacturing contributes to the global warming potential.

6.4 Environmental Impact comparison between the Laundry and School t-shirt lifetime of PLA, PET and Cotton fabrics

It is evident from the results in Figures 5.26 to 5.28 that increasing the efficiency of a product in the usage phase improves the environmental impact. When the lifetime of PET and cotton fabric was increased to 75 wash cycles for a whole year, the energy demand, water requirement and GWP reduced slightly. On the contrary, the environmental impact of PLA fabric increased with increased lifetime. This analysis agrees with the findings of Spielmann and Althaus (2007), who demonstrated that increasing the lifetime of a product does not automatically make up for the environmental impacts resulting at use stages.

Further analysis (Figures 5.21, 5.23, 5.25) to identify areas and process associated with the increased environmental impact only showed that there was no difference in the water demand or the GWP between the experimental and the school t-shirt lifetime (see Appendix 18). However, further analysis of the energy requirement showed that energy from nuclear sources more than doubled for all the fabrics. This is subject to further research outside the scope of this study to determine the reason for this increase. However, it is apparent that the main manufacturers of PLA (Cargill Dow) have identified this, hence the objective to reduce the fossil energy use from 54 MJ/kg to about 7 MJ/kg and the greenhouse gasses from +1.8 down to −1.7 kg CO_2 equivalents/kg PLA (Madhavan Nampoothiri *et al.* 2010).

Having established that the laundry lifetime of typical school t-shirt is about 75 wash cycles per year, and the experimental laundry lifetime of a 0.25kg PLA, PET and cotton fabric sample was 35, 42 and 43 wash cycles, a functional unit (the weight of fabric required up to 75 laundry cycles) was calculated using Equation 6. The system flow for the production of a school t-shirt lasting 75 wash cycles is shown in Figures 7.1, 7.2, and 7.3.

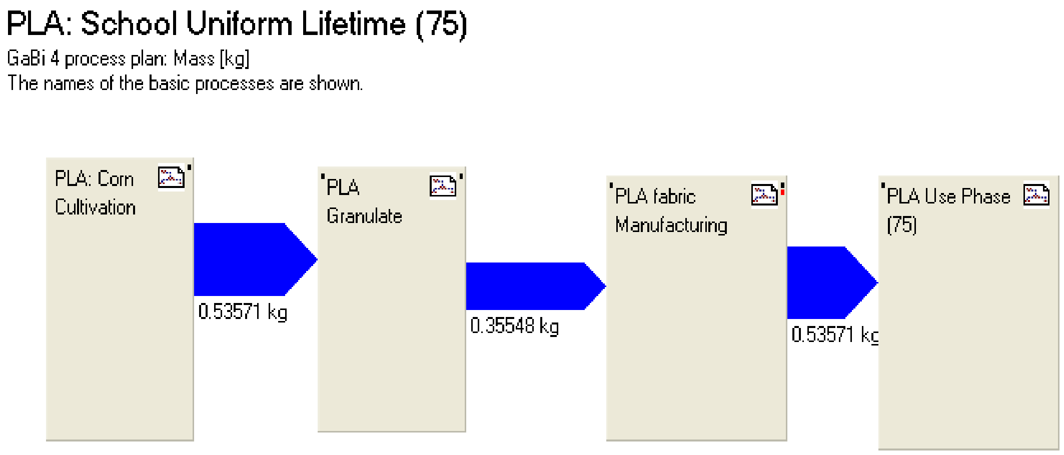

Figure 6.1: GaBi 4 analysis of the system flow for PLA uniform from the cradle-to-usage life cycle, used for the whole year of 75 laundry cycles

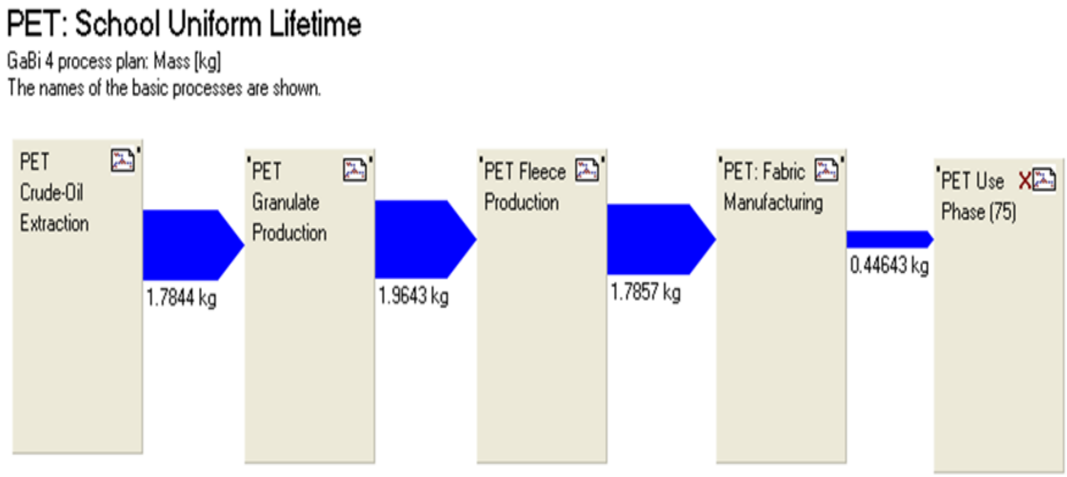

Figure 6.2: GaBi 4 analysis of the system flow for PET uniform from the cradle-to-usage life cycle, used for the whole year of 75 laundry cycles

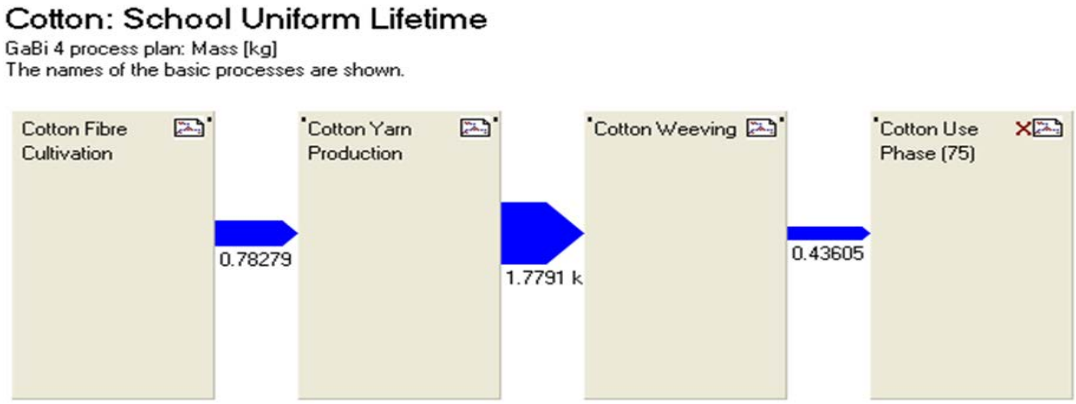

Figure 6.3: GaBi 4 analysis of the system flow for the Cotton uniform from the cradle-to-usage life cycle, used for the whole year of 75 laundry cycles

For PLA fabric 0.54kg of corn is required to produce; 0.34kg polylactide granulates, and consequently a 0.54kg t-shirt. For PET fabric 1.78kg of crude oil is required to produce; 1.96kg PET granulates, 1.78kg of fleece and consequently a 0.45kg t-shirt. While cotton fabric requires 0.78kg of cotton fibre to produce, 1.78kg cotton yarn, and consequently a 0.44kg t-shirt.

It is clear from Figure 5.11 that the energy demand for 0.54kg of PLA is essentially the same as 0.44kg of PET or cotton school t-shirt, which is not consistent with the result presented for the laundry lifetime. One possible reason could be that the functional unit of the PLA school t-shirt is almost double 0.25kg. In addition, the similarity could be due to the same number of wash cycles. However, when the starting material was considered (Figure 7.1-7.3), 0.54kg of corn was required to produce 0.54kg of PLA t-shirt, in contrast to 1.78kg of crude oil and 0.78kg of cotton seed required to produce a lower 0.44kg t-shirt. This implies that increasing the laundry lifetime and the durability of PLA to last up to 75 wash cycles, makes it comparable to PET and cotton in terms of total energy demand.

On the other hand, the GWP which should be directly linked to the quantity of energy use (Brentrup *et al.* 2004), was about 8-15% lower for PLA school t-shirt compared to PET or cotton. This analysis is consistent with the result presented in Figure 5.3 for the experimental laundry lifetime of the fabrics. However it is contradictory to what was expected since the global warming potential is directly related to the high amount of energy required during the life cycle of a product. As shown in Figure 5.6, the total water demand for cotton school t-shirt is twice that of PLA and PET school t-shirt. This analysis is almost similar to the result presented in Figure 5.5 for the experimental laundry lifetime of the fabrics. Further investigation revealed that the breakdown of the water requirement for the different processes of each fabric throughout their school t-shirt life cycle is similar to Figure 5.6.

6.5 Limitations

The results have been affected by several limitations, including the assumption of the average UK consumer habit of one load, mixed mode laundry. Also, due to time limitations, all the fabrics were washed together, which could have affected the result of the fabric laundry performance had they been dyed materials. Although the function of the fabric was specified, the material content and rate of change of fashion or style are not insignificant where durability and life expectancy is concerned. Each fabric responded differently to the laundry regime due to the different nature and characteristics of the fabrics (Table 3.1). Cotton absorbs more water, as a result, it will take a longer time to dry than PET and PLA. This could have influenced the result of the mechanical test for cotton fabric. One limitation which could have had a much wider implication on the outcome of this research is the different constituents, properties and performance of the fabrics. As different manufacturers made them, they could not have come from the same manufacturing batches. This limitation was overcome by washing larger samples of the material before cutting them to the same and consistent size for the mechanical test (see Section 3.2.1: Pilot test). The equipment used (washing machine, tumble-dryer and Instron tensile tester) and human errors were assumed to be random and had no significant influence on the results of the experiments. Since the laundry conditions simulated household laundering, all fabrics types were washed together. This assumption also applied to the input and output inventory analysis of the laundry use phase. The study assumed that they would be similar to all three fabrics due to the mixed mode laundry method, therefore, were excluded from the inventory. In conclusion, though the laundry regime used in this study has limited efficacy in predicting fabric durability and lifetime, it was able to show that fabric quality plays a vital role in the overall lifetime of the fabrics. Alongside, environmental impact associated with inferior fabrics, manufacturers should also invest in the production of quality material.

7 CONCLUSION

This study was set out to examine the potential benefits of adopting polylactic acid (PLA) as an alternative to cotton and polyethylene terephthalate (PET) and to explore the laundry durability and environmental performance of the fabrics from ‘cradle to usage’. The study also sought to determine, through changes in the tensile properties, the number of laundry cycles that best define the fabrics’ life expectancy:to evaluate and compare the cradle-to-usage environmental impact of polylactic acid, cotton and polyethylene terephthalate fabric, using tensile properties as indicators of fabric performance, and also to assess the suitability of PLA as a substitute for Cotton or PET on the basis of life cycle assessment.

The main findings of this study are highlighted in the results (Chapters 4 and 5) where the load-extension performance of PLA, PET and cotton was investigated to determine the number of laundry cycles that best defines the fabrics’ life expectancy. Also the influence of the laundry cycles and treatments on the tensile properties and performance were investigated in Chapter 4. Chapter 5 presents the results of the life cycle environmental impact assessment where the lifetime laundry indicator determined using the tensile properties and load-extension performance of the fabrics was incorporated into the life cycle model.

In summary, the laundry regime resulted in a significant level of impact on the cotton compared to the PLA fabric in the different laundry treatments with or without softener. However, the PET fabric showed no significant effect from the laundry regime nor the laundry treatments (Figure 7.1).

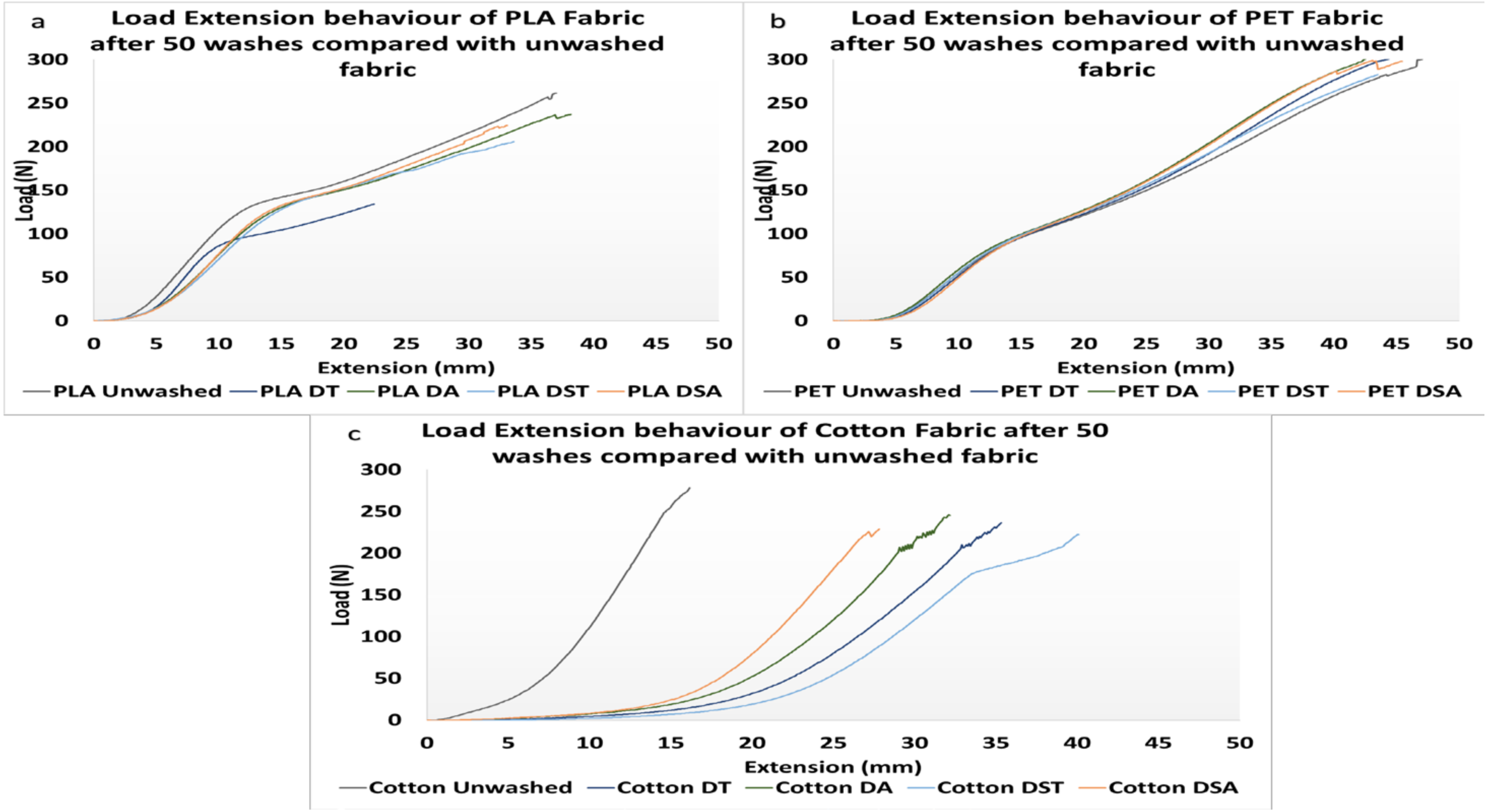

Figure 7.1: Cotton showed the greatest influence with, 5.1% decrease in the yield load for DST, followed by 3.1% for both DT and DA, and 2% for DSA. For PLA, DT resulted in a 4.9% decrease, whereas DA, DSA and DST resulted in a less than 1% decrease in yield load. For PET the different laundry procedures did not to alter the linear elasticity of PET fabric

In conclusion, subjecting PLA, PET, and cotton fabric to a laundry regime (one, three, six, 10, 30, and 50 wash cycles) in different laundry conditions results in a significant level of impact on cotton fabric (all laundry conditions) and PLA (tumble-dried, with or without softener). From a practical standpoint, the result of this study suggests that tumble-drying should be avoided; however, the use of softeners during the laundry plus air-drying seems to provide stability for PLA and PET fabrics. The influence on the cotton fabric was more from the drying process than the use or absence of softener. This reinforces the conclusion that tumble-drying should be avoided if possible.

Based on the mechanical properties, the number of laundry cycles that best defines the fabrics life expectancy for PLA fabric showed a lower lifetime (35 washes/life cycle) compared to PET and cotton (42 and 43 washes/life cycle respectively). The proportion of the total impact of the three fabrics (Table 7.1) showed that PLA offers a low environmental burden than PET and cotton.

Table 7.1: Summary of the laundry lifetime impact assessment

Impact category	**PLA (%)**	**PET (%)**	**Cotton (%)**
Energy Demand	**28.5**	**34.9**	**36.5**
Water Consumption	**21**	**26.4**	**53**
GWP Contribution	**22**	**35.2**	**43**

The functional unit was calculated from Equation 6 using a typical school t-shirt as the end use of 75 laundry cycles per year. The overall environmental impact of cotton decreased by 2%, PET decreased by about 1.2%, while PLA increased by 3% when the laundry lifetime was increased. In assessing the life cycle performance of PLA fabric in comparison to PET and cotton, it is clear that the quantity of input material into the production stages of these fabrics can alter their overall environmental impact. For example, the amount or the quality of PLA granule and raw fabric used to produce a t-shirt can change the life cycle inventory. When the environmental impact differences between the experimental lifetime and the 75 wash cycles of a school t-shirt were assessed, PLA offered environmental benefits compared to PET and cotton. Also from the comparative life cycle assessment of the laundry lifetime and the school t-shirt use of 75 washes per year. Cotton had an average of about 4-5 times higher environmental impact than PET and PLA.

Although the use phase was the dominant contributor to environmental impacts, this phase has the potential to improve the environmental performance if the fabric were produced to last longer. Though the bulk of the energy used and GWP potential for PLA is associated with the production of fabric from lactic acid; therefore, fabric enhancement will only lead to more energy and CO_2 emission per functional unit of PLA produced. However, it is evident that the longer the lifetime of the product, this will offset the overall environmental impact of the fabrics.

Finally, the life cycle scenarios (Laundry and school t-shirt lifetime) used to illustrate the environmental performance shows that there is a possibility of reducing the environmental impact of the fabrics' life cycle by enhancing the durability of the fabrics. However, results from this study concluded that enhancing the fabric to increase its laundry lifetime does not automatically decrease the environmental impacts; nevertheless it has demonstrated that that even a small rise in the lifetime of PLA fabric can make it comparable and competitive with PET and cotton fabric. Also PLA demonstrated similar mechanical properties to PET and therefore would be a valuable substitute, with a sustainably low environmental burden. PLA demonstrates a better alternative to cotton in all aspects and is recommended as a suitable replacement due to its potential water, energy and CO_2 emission savings.

7.1 Recommendations and Future Research

Based on the life cycle performance carried out on the studied fabrics, the processes that contribute most to the environmental impact are the use phase and the manufacturing phase. During the use phase, it is recommended that reducing the washing temperature, (i.e reducing the need to heat water for laundry) and avoiding the use of tumble-drying will significantly influence the overall environmental impact of the fabrics. Also, washing at the maximum washing load, using the recommended quantity of detergent will not only avoid wastage but optimise the laundry process and eventually influence the environmental performance of the fabric positively. During the fabric manufacturing process, the use of heat and cooling water present significant environmental impacts. It is recommended that, in the long run, enhancing quality and durability of the fabrics by increasing the material input will significantly reduce the environmental impact.

From the result of the current study, one aspect that requires further research is with the life cycle inventory for both the agricultural process and the production of lactide from corn. Since this study used GaBi 4 modelling, future research could try other software such as SimaPro and Quantis with different methods to evaluate the consistency of the results for PLA fabric. The current study only focused on the cradle to usage of PLA fabric compared with PET and cotton, however, further research could expand this to include the end of life scenarios such as recycling, composting and incineration or anaerobic digestion with energy recovery. PLA could have additional environmental benefits as the energy recovered could offset impacts associated with the energy intensive process as the use phase.

Due to the limited number of studies or LCAs on PLA versus other conventional materials, there is a need for more research to keep up with the pace of growing interest in the application of PLA as textiles. Another aspect that would need further research is the efficiency of PLA during its usage phase. From the result of the current study, increasing the lifetime of PLA fabric up to 75 wash cycles did not improve the overall environmental impact. On the contrary the environmental impact of PET and cotton reduced with an increase in lifetime. As the reason for the difference in result was not quite clear and due to time constraint, this area is open for further investigation.

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Appendices

Appendix 1: Summary of statistics and standard deviation of tensile modulus for PLA, PET and cotton by laundry treatment and number of laundry cycles

Fabric Type	Laundry Treatments	Number of Laundry Cycles														*p* value	R^2
		0		1		3		6		10		30		50			
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
PLA	**DT**	15.76	0.33	17.06	0.74	16.84	0.32	16.04	0.21	16.52	1.32	17.54	1.09	16.72	0.58	0.017	0.20
	DA	15.76	0.33	14.84	0.35	14.66	0.32	15.20	0.12	14.04	0.27	14.24	0.33	13.84	0.73	0.000	0.74
	DSA	15.76	0.33	15.44	0.15	15.62	0.18	15.82	0.22	15.82	0.08	16.08	0.36	14.70	0.24	0.000	0.08
	DST	15.76	0.33	15.92	0.23	15.80	0.59	15.68	0.13	15.74	0.18	16.22	0.50	14.16	0.99	0.000	0.24
PET	**DT**	10.70	0.12	12.56	0.30	11.54	0.15	11.06	0.37	11.62	0.18	11.22	0.08	10.98	0.24	0.000	0.05
	DA	10.70	0.12	11.60	0.22	11.62	0.24	11.14	0.23	11.12	0.25	11.54	0.23	11.26	0.11	0.000	0.06
	DSA	10.70	0.12	11.58	0.23	11.68	0.23	12.40	0.29	12.18	0.24	11.44	0.36	11.84	0.68	0.000	0.25
	DST	10.70	0.12	11.18	0.16	11.32	0.22	11.34	0.22	11.18	0.13	11.36	0.24	11.36	0.11	0.000	0.51
Cotton	**DT**	29.34	1.38	29.64	1.81	24.70	0.37	22.10	1.70	17.12	0.54	17.12	0.87	16.42	0.43	0.000	0.92
	DA	29.34	1.38	19.02	0.90	19.30	1.89	20.28	0.30	16.44	0.21	20.22	1.11	17.44	1.21	0.000	0.43
	DSA	29.34	1.38	17.38	1.01	18.08	1.13	18.18	1.13	16.82	1.39	20.30	1.12	21.24	1.00	0.000	0.12
	DST	29.34	1.38	26.00	1.04	24.72	2.59	22.36	0.72	19.00	0.46	18.04	0.44	15.54	0.67	0.000	0.98

Appendix 2: ANOVA statistics for tensile modulus of PLA, PET and cotton fabric ($p<0.001$)

	PLA					PET					Cotton				
Source	**Partial SS**	**df**	**MS**	**F**	*p* **value**	**Partial SS**	**df**	**MS**	**F**	*p* **value**	**Partial SS**	**df**	**MS**	**F**	*p* **value**
Model	112	27	4.1	16	0.000	30	27	1.10	18	0.000	2954	27	109	78	0.000
Number of laundry cycles	16	6	2.7	10	0.000	12	6	1.95	32	0.000	2057	6	343	244	0.000
Laundry treatment	69	3	23	88	0.000	5	3	1.56	25	0.000	140	3	47	33	0.000
Interaction	27	18	1.5	6	0.000	13	18	0.73	12	0.000	756	18	42	30	0.000
Residual	29	112	0.3			7	112	0.06			157	112	1		
Total	141	139	1.0			36	139	0.26			3111	139	22		

Appendix 3: Summary of statistics and standard deviation of tensile strength for PLA, PET and cotton by laundry treatment and number of laundry cycles

Fabric Type	Laundry Treatments	Number of Laundry Cycles														p-value	R^2
		0		1		3		6		10		30		50			
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
PLA	DT	8.82	0.32	8.82	0.15	8.30	0.36	8.31	0.32	4.99	0.68	4.95	0.77	4.94	0.48	0.000	0.94
	DA	8.82	0.32	8.42	0.39	8.43	0.24	8.08	0.37	7.74	0.68	7.93	0.48	7.88	0.62	0.012	0.42
	DSA	8.82	0.32	7.54	1.32	8.05	0.61	7.97	0.61	7.82	0.25	7.73	0.65	7.29	0.55	0.05	0.34
	DST	8.82	0.32	8.74	0.19	8.63	0.42	8.72	0.22	8.72	0.09	4.60	0.47	7.07	0.26	0.000	0.96
PET	DT	10.05	0.33	10.46	0.13	10.38	0.18	10.08	0.39	10.23	0.28	10.61	0.18	10.66	0.52	0.020	0.39
	DA	10.05	0.33	10.34	0.34	10.72	0.40	10.59	0.27	10.26	0.46	10.40	0.22	10.42	0.21	0.070	0.32
	DSA	10.05	0.33	10.22	0.24	9.83	0.36	10.70	0.08	10.57	0.26	10.44	0.15	10.52	0.13	0.000	0.64
	DST	10.05	0.33	10.43	0.13	10.43	0.28	10.45	0.18	10.35	0.09	10.50	0.29	10.47	0.16	0.05	0.34
Cotton	DT	6.32	0.06	5.73	0.33	5.71	0.18	5.49	0.07	5.38	0.24	5.43	0.05	5.37	0.04	0.000	0.80
	DA	6.32	0.06	5.27	0.04	5.61	0.10	5.71	0.13	4.79	0.12	5.62	0.12	5.64	0.11	0.000	0.96
	DSA	6.32	0.06	5.09	0.08	4.88	0.07	4.64	0.12	4.60	0.18	5.36	0.23	5.22	0.04	0.000	0.96
	DST	6.32	0.06	5.71	0.10	5.62	0.06	5.69	0.09	5.47	0.06	5.38	0.05	5.16	0.14	0.000	0.94

Appendix 4: ANOVA statistics for tensile strength of PLA, PET and cotton fabric ($p<0.001$)

	PLA					PET					Cotton				
Source	Partial SS	df	MS	F	p value	Partial SS	df	MS	F	p value	Partial SS	df	MS	F	p value
Model	226	27	8	33	0.000	7	27	0.26	3	0.000	30	27	1.09	68	0.000
Number of laundry cycles	107	6	18	70	0.000	3	6	0.50	6	0.000	18	6	3.04	189	0.000
Laundry treatment	27	3	9	35	0.000	0.09	3	0.03	0	0.780	5	3	1.77	110	0.000
Interaction	92	18	5	20	0.000	4	18	0.22	3	0.001	6	18	0.33	21	0.000
Residual	29	112	0.26			9	112	0.08			2	112	0.02		
Total	255	139	2			16	139	0.11			31	139	0.23		

Appendix 5: Summary of statistics and standard deviation of load at break for PLA, PET and cotton by laundry treatment and number of laundry cycles

Fabric Type	Laundry Treatments	Number of Laundry Cycles														*p* value	R^2
		0		1		3		6		10		30		50			
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
PLA	**DT**	253.60	9.13	253.62	4.41	238.64	10.41	238.82	9.33	143.36	19.68	142.24	22.14	142.02	13.87	0.000	0.94
	DA	253.60	9.13	241.94	11.13	242.34	6.76	232.12	10.50	222.56	19.56	227.96	13.75	226.68	17.78	0.012	0.42
	DSA	253.60	9.13	216.72	37.85	231.36	17.52	229.22	17.59	224.92	7.27	222.20	18.67	209.72	15.74	0.05	0.34
	DST	253.60	9.13	251.34	5.49	248.26	11.94	250.74	6.25	250.72	2.47	132.18	13.53	203.18	7.49	0.000	0.96
PET	**DT**	288.76	9.46	300.82	3.73	298.50	5.00	289.94	11.15	294.00	7.89	305.06	5.22	306.48	14.89	0.020	0.40
	DA	288.76	9.46	297.28	9.57	308.28	11.43	304.42	7.71	295.10	13.06	298.86	6.39	299.56	6.15	0.070	0.32
	DSA	288.76	9.46	293.94	6.89	282.64	10.51	307.74	2.34	303.78	7.32	300.20	4.16	302.34	3.69	0.000	0.64
	DST	288.76	9.46	299.80	3.80	299.78	8.10	300.48	5.09	297.56	2.48	301.92	8.15	301.00	4.77	0.05	0.34
Cotton	**DT**	276.60	2.49	250.88	14.56	249.70	7.71	240.20	3.02	235.42	10.61	237.56	1.91	235.08	1.59	0.000	0.80
	DA	276.60	2.49	230.50	2.01	245.32	4.27	250.02	5.46	209.56	5.41	245.78	5.16	246.94	4.48	0.000	0.96
	DSA	276.60	2.49	222.76	3.53	213.50	3.01	203.30	5.25	201.36	7.86	234.62	9.91	228.58	1.77	0.000	0.96
	DST	276.60	2.49	249.86	4.49	246.04	2.64	248.92	4.16	239.32	2.36	235.30	2.20	225.50	6.04	0.000	0.94

Appendix 6: ANOVA statistics for load at break of PLA, PET and cotton fabric ($p<0.001$)

	PLA					PET					Cotton				
Source	**Partial SS**	**df**	**MS**	**F**	***p* value**	**Partial SS**	**df**	**MS**	**F**	***p* value**	**Partial SS**	**df**	**MS**	**F**	***p* value**
Model	187048	27	6928	33	0.000	5769	27	214	3	0.000	56435	27	2090	68	0.000
Number of laundry cycles	88803	6	14801	70	0.000	2490	6	415	6	0.000	34888	6	5815	190	0.000
Laundry treatment	22216	3	7405	35	0.000	70	3	23	0	0.781	10165	3	3388	111	0.000
interaction	76029	18	4224	20	0.000	3209	18	178	3	0.001	11382	18	632	21	0.000
Residual	23758	112	212			7260	112	65			3426	112	31		
Total	210806	139	1517			13029	139	94			59861	139	431		

Appendix 7: Summary of statistics and standard deviation of percentage extension at break for PLA, PET and cotton by laundry treatment and number of laundry cycles

Fabric Type	Laundry Treatments	Number of Laundry Cycles														p-value	R^2
		0		1		3		6		10		30		50			
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.		
PLA	DT	29%	0.01	25%	0.02	25%	0.03	26%	0.01	19%	0.01	19%	0.03	20%	0.02	0.000	0.80
	DA	29%	0.01	29%	0.01	28%	0.02	27%	0.02	29%	0.03	29%	0.03	29%	0.03	0.84	0.08
	DSA	29%	0.01	25%	0.04	28%	0.03	26%	0.02	27%	0.02	26%	0.02	25%	0.02	0.20	0.24
	DST	29%	0.01	28%	0.03	29%	0.01	30%	0.02	31%	0.01	19%	0.03	27%	0.02	0.000	0.79
PET	DT	37%	0.02	31%	0.01	34%	0.01	37%	0.05	33%	0.01	36%	0.00	36%	0.02	0.000	0.54
	DA	37%	0.02	33%	0.01	35%	0.02	35%	0.02	33%	0.02	33%	0.01	37%	0.03	0.015	0.41
	DSA	37%	0.02	32%	0.02	37%	0.05	37%	0.03	38%	0.03	37%	0.01	35%	0.02	0.04	0.36
	DST	37%	0.02	39%	0.01	40%	0.03	39%	0.02	38%	0.01	39%	0.01	39%	0.01	0.10	0.29
Cotton	DT	14%	0.03	18%	0.01	23%	0.01	22%	0.02	26%	0.01	26%	0.01	28%	0.01	0.000	0.91
	DA	14%	0.03	23%	0.01	23%	0.01	23%	0.00	26%	0.01	22%	0.01	25%	0.01	0.000	0.89
	DSA	14%	0.03	26%	0.01	26%	0.02	24%	0.01	24%	0.02	24%	0.00	24%	0.03	0.000	0.83
	DST	14%	0.03	19%	0.01	17%	0.00	22%	0.01	25%	0.02	28%	0.03	34%	0.02	0.000	0.94

Appendix 8: ANOVA statistics for percentage extension of PLA, PET and cotton fabric ($p<0.001$)

	PLA					PET					Cotton				
Source	Partial SS	df	MS	F	p value	Partial SS	df	MS	F	p value	Partial SS	df	MS	F	p value
Model	0.149	27	0.006	11	0.000	0.073	27	0.003	6	0.000	0.309	27	0.011	40	0.000
Number of laundry cycles	0.040	6	0.007	13	0.000	0.014	6	0.002	5	0.000	0.231	6	0.038	136	0.000
Laundry treatment	0.051	3	0.017	33	0.000	0.035	3	0.012	25	0.000	0.001	3	0.000	1	0.482
Interaction	0.059	18	0.003	6	0.000	0.024	18	0.001	3	0.000	0.077	18	0.004	15	0.000
Residual	0.058	112	0.001			0.052	112	0.000			0.032	112	0.000		
Total	0.207	139	0.001			0.125	139	0.001			0.340	139	0.002		

Appendix 9: Summary of statistics on the Yield load for PLA, PET and cotton by laundry treatment and number of laundry cycles

Laundry Treatment	Laundry Cycles	Yield load		
		PLA	PET	Cotton
Laundry and Tumble dried	0	126.6	80.0	252.3
	1	133.7	87.9	209.3
	3	127.0	82.1	195.7
	6	127.1	80.8	178.2
	10	92.9	79.2	195.8
	30	90.6	80.3	213.5
	50	87.9	80.3	206.8
Laundry and Air Dried	0	126.6	80.0	252.3
	1	131.2	87.2	207.8
	3	128.3	81.3	186.4
	6	127.6	79.2	218.0
	10	121.9	79.4	182.1
	30	122.8	79.4	203.3
	50	121.9	79.6	206.8
Laundry, Softener and Tumble dried	0	126.6	80.0	252.3
	1	132.5	80.6	212.5
	3	127.0	81.2	213.5
	6	126.2	81.2	230.1
	10	125.7	80.8	206.0
	30	80.3	79.6	172.0
	50	124.1	78.5	177.0
Laundry, Softener and Air Dried	0	126.6	80.0	252.3
	1	129.9	80.1	193.2
	3	127.2	76.0	154.0
	6	126.6	75.8	160.8
	10	126.0	80.1	177.2
	30	124.1	80.9	212.1
	50	124.05	80.80	224.33

Appendix 10: Summary of statistics of Extension at yield for PLA, PET and cotton by laundry treatment and number of laundry cycles

Laundry Treatment	Laundry Cycles	Extension at Yield		
		PLA	PET	Cotton
Laundry and Tumble dried	0	11.92	12.67	14.83
	1	11.08	11.58	21.17
	3	12.58	12.58	24.42
	6	13.58	12.17	24.17
	10	11.08	11.75	30.20
	30	10.25	12.42	31.25
	50	10.25	12.83	33.08
Laundry and Air Dried	0	11.92	12.67	14.83
	1	14.08	12.17	27.67
	3	13.42	11.75	25.58
	6	13.42	12.33	27.08
	10	14.58	12.08	29.83
	30	13.75	11.75	25.58
	50	13.83	11.90	29.08
Laundry, Softener and Tumble dried	0	11.92	12.67	14.83
	1	12.50	12.58	22.17
	3	12.42	12.58	20.25
	6	12.33	12.83	25.50
	10	13.33	12.75	27.75
	30	9.58	12.50	30.25
	50	16.33	12.25	37.92
Laundry, Softener and Air Dried	0	11.92	12.67	14.83
	1	12.67	11.75	30.17
	3	13.33	11.75	28.08
	6	12.50	12.58	26.08
	10	12.83	12.25	27.42
	30	12.67	14.83	28.83
	50	13.75	12.92	27.08

Appendix 11: Result of the Tukey pairwise comparison of the tensile modulus of each laundry cycle with the unwashed material. Highlighted boxes show the significance (p<0.001) difference between the unwashed and the corresponding laundry cycle.

Laundry Treatments	Laundry Cycles	PLA			PET			Cotton		
		Contrast	t	P>t	Contrast	t	P>t	Contrast	t	P>t
DT	1	1.29	2.52	0.014	1.87	3.64	0.000	0.27	0.53	0.595
	3	1.09	2.12	0.037	0.85	1.66	0.101	-4.68	-9.11	0.000
	6	0.28	0.54	0.592	0.34	0.67	0.507	-7.27	-14.15	0.000
	10	0.75	1.45	0.150	0.91	1.77	0.080	-12.25	-23.84	0.000
	30	1.77	3.45	0.001	0.53	1.04	0.302	-12.26	-23.86	0.000
	50	0.95	1.85	0.068	0.28	0.55	0.582	-12.93	-25.17	0.000
DA	1	-0.92	-2.06	0.042	0.90	2.01	0.047	-10.34	-23.06	0.000
	3	-1.09	-2.42	0.018	0.93	2.07	0.042	-10.07	-22.47	0.000
	6	-0.57	-1.28	0.205	0.42	0.93	0.354	-9.07	-20.23	0.000
	10	-1.71	-3.81	0.000	0.42	0.93	0.354	-12.91	-28.81	0.000
	30	-1.54	-3.43	0.001	0.85	1.89	0.062	-9.13	-20.38	0.000
	50	-1.90	-4.24	0.000	0.56	1.24	0.217	-11.91	-26.58	0.000
DSA	1	-0.33	-0.72	0.472	0.91	2.00	0.049	-11.99	-26.26	0.000
	3	-0.13	-0.28	0.783	1.01	2.21	0.030	-11.29	-24.74	0.000
	6	0.05	0.11	0.910	1.72	3.77	0.000	-11.18	-24.49	0.000
	10	0.06	0.14	0.889	1.50	3.29	0.001	-12.53	-27.45	0.000
	30	0.32	0.69	0.491	0.73	1.60	0.113	-9.04	-19.81	0.000
	50	-1.06	-2.32	0.023	1.17	2.56	0.012	-8.11	-17.76	0.000
DST	1	0.16	0.33	0.746	0.28	0.55	0.581	-3.34	-6.71	0.000
	3	0.04	0.09	0.930	0.42	0.84	0.401	-4.65	-9.34	0.000
	6	-0.09	-0.18	0.857	0.45	0.90	0.371	-7.00	-14.06	0.000
	10	0.00	0.00	1.000	0.27	0.55	0.586	-10.36	-20.81	0.000
	30	0.46	0.92	0.362	0.45	0.90	0.369	-11.34	-22.78	0.000
	50	-1.58	-3.18	0.002	0.47	0.94	0.352	-13.82	-27.76	0.000

Appendix 12: Result of the Tukey pairwise comparison of the tensile strength of each laundry cycle with the unwashed material. Highlighted boxes show the significance (p<0.001) difference between the unwashed and the corresponding laundry cycle.

Laundry Treatments	Laundry Cycles	PLA			PET			Cotton		
		Contrast	t	P>t	Contrast	t	P>t	Contrast	t	P>t
DT	1	-0.404	-1.91	0.059	0.294	1.39	0.168	-1.052	-4.98	0.000
	3	-0.39	-1.85	0.068	0.676	3.2	0.002	-0.714	-3.38	0.001
	6	-0.744	-3.52	0.001	0.54	2.56	0.012	-0.608	-2.88	0.005
	10	-1.078	-5.1	0.000	0.216	1.02	0.310	-1.532	-7.25	0.000
	30	-0.892	-4.22	0.000	0.35	1.66	0.101	-0.704	-3.33	0.001
	50	-0.938	-4.44	0.000	0.374	1.77	0.080	-0.678	-3.21	0.002
DA	1	1.91E-07	0	1.000	0.416	1.88	0.063	-0.588	-2.66	0.009
	3	-0.522	-2.36	0.020	0.338	1.53	0.130	-0.614	-2.78	0.007
	6	-0.514	-2.33	0.022	3.80E-02	0.17	0.864	-0.832	-3.77	0.000
	10	-3.834	-17.37	0.000	0.18	0.82	0.417	-0.942	-4.27	0.000
	30	-3.874	-17.55	0.000	0.564	2.55	0.012	-0.892	-4.04	0.000
	50	-3.88	-17.57	0.000	0.616	2.79	0.007	-0.948	-4.29	0.000
DSA	1	-1.28	-4.7	0.000	0.178	0.65	0.515	-1.23	-4.52	0.000
	3	-0.774	-2.84	0.006	-0.218	-0.8	0.425	-1.442	-5.3	0.000
	6	-0.846	-3.11	0.003	0.656	2.41	0.018	-1.678	-6.17	0.000
	10	-0.998	-3.67	0.000	0.522	1.92	0.059	-1.72	-6.32	0.000
	30	-1.092	-4.01	0.000	0.396	1.45	0.149	-0.96	-3.53	0.001
	50	-1.526	-5.61	0.000	0.47	1.73	0.088	-1.098	-4.03	0.000
DST	1	-0.078	-0.55	0.585	0.382	2.69	0.009	-0.612	-4.3	0.000
	3	-0.186	-1.31	0.194	0.382	2.69	0.009	-0.698	-4.91	0.000
	6	-0.098	-0.69	0.493	0.406	2.86	0.005	-0.632	-4.44	0.000
	10	-0.098	-0.69	0.493	0.304	2.14	0.035	-0.852	-5.99	0.000
	30	-4.222	-29.69	0.000	0.454	3.19	0.002	-0.946	-6.65	0.000
	50	-1.752	-12.32	0.000	0.424	2.98	0.004	-1.166	-8.2	0.000

Appendix 13: Result of the Tukey pairwise comparison of the percentage extension after each laundry cycle with the unwashed material. Highlighted boxes show the significance (p<0.001) difference between the unwashed and the corresponding laundry cycle.

Laundry Treatments	Laundry Cycles	PLA			PET			Cotton		
		Contrast	t	P>t	Contrast	t	P>t	Contrast	t	P>t
DT	1	-0.036	-2.95	0.004	-0.054	-4.43	0.000	0.044	3.61	0.001
	3	-0.036	-2.95	0.004	-0.03	-2.46	0.016	0.088	7.22	0.000
	6	-0.024	-1.97	0.052	0.008	0.66	0.513	0.084	6.89	0.000
	10	-0.096	-7.88	0.000	-0.036	-2.95	0.004	0.124	10.17	0.000
	30	-0.096	-7.88	0.000	-0.008	-0.66	0.513	0.12	9.84	0.000
	50	-0.088	-7.22	0.000	-0.002	-0.16	0.870	0.138	11.32	0.000
DA	1	-5.22E-18	0	1.000	-0.032	-2.56	0.012	0.094	7.52	0.000
	3	-0.004	-0.32	0.750	-0.02	-1.6	0.113	0.092	7.36	0.000
	6	-0.018	-1.44	0.154	-0.012	-0.96	0.340	0.09	7.2	0.000
	10	-0.002	-0.16	0.873	-0.032	-2.56	0.012	0.124	9.92	0.000
	30	-0.002	-0.16	0.873	-0.032	-2.56	0.012	0.086	6.88	0.000
	50	0.006	0.48	0.632	0.004	0.32	0.750	0.112	8.96	0.000
DSA	1	-0.034	-2.23	0.028	-0.042	-2.76	0.007	0.118	7.75	0.000
	3	-0.008	-0.53	0.601	0.006	0.39	0.695	0.118	7.75	0.000
	6	-0.03	-1.97	0.052	0.008	0.53	0.601	0.1	6.57	0.000
	10	-0.022	-1.44	0.152	0.014	0.92	0.360	0.098	6.44	0.000
	30	-0.03	-1.97	0.052	1.19E-08	0	1.000	0.104	6.83	0.000
	50	-0.038	-2.5	0.015	-0.02	-1.31	0.193	0.098	6.44	0.000
DST	1	-0.004	-0.34	0.736	0.022	1.86	0.066	0.054	4.57	0.000
	3	0.004	0.34	0.736	0.036	3.04	0.003	0.034	2.88	0.005
	6	0.008	0.68	0.501	0.024	2.03	0.046	0.078	6.6	0.000
	10	0.02	1.69	0.094	0.018	1.52	0.132	0.11	9.3	0.000
	30	-0.096	-8.12	0.000	0.026	2.2	0.031	0.142	12.01	0.000
	50	-0.02	-1.69	0.094	0.022	1.86	0.066	0.198	16.75	0.000

Appendix 14: Tensile properties at number of laundry cycles fabrics showed significant changes to laundry treatments

Fabric Type	Tensile Properties	Unwashed	DT	DA	DSA	DST
PLA	Tensile Modulus	15.76	17.54	14.04	14.16	15.74
	Tensile Strength	8.82	4.99	8.08	7.54	4.60
	Percentage Extension (%)	0.29	0.25	0.29	0.26	0.27
PET	Tensile Modulus	10.70	10.98	11.26	12.40	11.36
	Tensile Strength	10.05	10.61	10.72	10.70	10.43
	Percentage Extension (%)	0.37	0.37	0.33	0.35	0.39
Cotton	Tensile Modulus	29.34	29.64	19.02	17.38	26
	Tensile Strength	6.32	5.73	5.27	5.09	5.71
	Percentage Extension (%)	0.14	0.18	0.23	0.26	0.19

Appendix 15: Inventory analysis for the 'cradle to laundry-use-phase of 0.25kg of PLA fabric from the raw material production, through yarn production, textile weaving plant to its experimental laundry use life cycle of 10 wash cycles

Corn Cultivation, Harvesting and Drying			
Inputs	**Quantity**	**amount**	**unit**
Carbon dioxide [Renewable resources]	Mass	1.3723	kg
CH: green manure IP, until April [plant production]	Area	1.0777	sqm
CH: hoeing [work processes]	Area	1.08E+00	sqm
CH: maize drying [work processes]	Mass	0.40984	kg
CH: maize seed IP, at regional storehouse [seed]	Mass	0.002694	kg
CH: pesticide unspecified, at regional storehouse [Pesticide]	Mass	6.52E-06	kg
CH: slurry spreading, by vacuum tanker [work processes]	Volume	1.27E-03	m3
CH: solid manure loading and spreading, by hydraulic loader and spreader [work processes]	Mass	0.8379	kg
CH: sowing [work processes]	Area	1.0777	sqm
CH: tillage, harrowing, by spring tine harrow [work processes]	Area	2.1554	sqm
CH: tillage, ploughing [work processes]	Area	1.0777	sqm
CH transport, lorry 20-28t, fleet average [Street]	ton kilometre (tkm)	3.33E-03	tkm
CH: transport, tractor and trailer [work processes]	ton kilometre (tkm)	0.014098	tkm
CH: transport, van <3.5t [Street]	ton kilometre (tkm)	4.55E-05	tkm
MA: phosphate rock, as P2O5, beneficiated, dry, at plant [inorganics]	Mass	0.00075	kg
RER: urea, as N, at regional storehouse [organics]	Mass	0.001516	kg
Outputs	**Quantity**	**Amount**	
grain maize IP, at farm [plant production]	Mass	1.507	kg
Polylactide, granulate Production			
Inputs	**Quantity**	**amount**	**unit**
corn, at farm [plant production]	Mass	1.507	kg
electricity, low voltage, production UCTE, at grid [production mix]	Energy (net calorific value)	6.580747	MJ
transport, lorry >16t, fleet average [Street]	ton kilometre (tkm)	0.2	tkm
natural gas burned in industrial furnace >100kW [heating systems]	Energy (net calorific value)	18.46	MJ
natural gas, at long-distance pipeline [Appropriation]	Standard volume	0.0036	Nm3
naphtha, at refinery [fuels]	Mass	0.007	kg
light fuel oil burned in industrial furnace 1MW, non-modulating [heating systems]	Energy (net calorific value)	0.159	MJ
chemical plant, organics [organics]	Number of pieces	4.00E-10	pcs.
treatment, maize starch production effluent, to wastewater treatment, class 2 [wastewater treatment]	Volume	0.0032	m3
disposal, plastics, mixture, 15.3% water, to the sanitary landfill [sanitary landfill facility]	Mass	0.001	kg
disposal, hazardous waste, 25% water, to hazardous waste incineration [hazardous waste incineration]	Mass	0.0064	kg

Outputs	Quantity	Amount	
polylactide, granulate, at plant [polymers]	Mass	0.66357	kg
NMVOC (unspecified) [Group NMVOC to air]	Mass	0.001672	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	4.366821	MJ
PLA fabric Production (Melt Extrusion)			
Inputs	**Quantity**	**amount**	**unit**
disposal, plastics, mixture, 15.3% water, to municipal incineration [municipal incineration]	Mass	0.0241	kg
polylactide, granulate, at plant [polymers]	Mass	0.66357	kg
core board, at plant [packaging papers]	Mass	0.00732	kg
heat, at hard coal industrial furnace 1-10MW [heating systems]	Energy (net calorific value)	0.0751	MJ
heat, heavy fuel oil, at industrial furnace 1MW [heating systems]	Energy (net calorific value)	0.134	MJ
heat, natural gas, at industrial furnace >100kW [heating systems]	Energy (net calorific value)	0.601	MJ
lubricating oil, at plant [organics]	Mass	0.000105	kg
packaging box production unit [cardboard & corrugated board]	Number of pieces	1.40E-09	pcs.
particle board, outdoor use, at plant [Beneficiation]	Volume	2.15E-05	m3
solid bleached board, SBB, at plant [cardboard & corrugated board]	Mass	0.000976	kg
steam, for chemical processes, at plant [Auxiliary material]	Mass	0.058	kg
transport, lorry 3.5-16t, fleet average [Street]	ton kilometre (tkm)	0.0118	tkm
electricity, medium voltage, production UCTE, at grid [production mix]	Energy (net calorific value)	2.375981	MJ
Water [Water]	Mass	43.7	kg
Outputs	**Quantity**	**Amount**	
Fabric Sample [Textiles]	Mass	0.25	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	2.38	MJ
PLA Fabric Laundry (10 Wash Cycles)			
Inputs	**Quantity**	**amount**	**unit**
electricity, consumer mix [supply mix]	Energy (net calorific value)	216	MJ
Detergent [Operating materials]	Mass	0.45	kg
Fabric Sample [Textiles]	Mass	0.25	kg
tap water, at user [Appropriation]	Mass	690	kg

Appendix 16: Inventory analysis for the 'cradle to laundry use phase of 0.25kg of PET fabric from the raw material production, through yarn production, textile weaving plant to its experimental laundry use life cycle of 50 wash cycles.

Crude Oil Production			
Inputs	**Quantity**	**amount**	**unit**
CH: disposal, municipal solid waste, 22.9% water, to municipal incineration [municipal incineration]	Mass	3.62E-04	kg
CH: low active radioactive waste [waste treatment]	Volume	1.99E-09	m3
Crude oil ecoinvent [Crude oil (resource)]	Mass	9.98E-01	kg
GLO: chemicals inorganic, at plant [inorganics]	Mass	1.20E-06	kg
GLO: chemicals organic, at plant [organics]	Mass	8.94E-07	kg
GLO: discharge, produced water, onshore [Appropriation]	Mass	4.23E-01	kg
GLO: natural gas, sweet, burned in production flare [Appropriation]	Energy (net calorific value)	4.62E+00	MJ
GLO: natural gas, vented [Appropriation]	Standard volume	0.02192	Nm3
GLO: production plant crude oil, onshore [Appropriation]	Number of pieces	1.24E-10	pcs.
GLO: well for exploration and production, onshore [Appropriation]	Length	4.06E-06	m
NO: sweet gas, burned in gas turbine, production [power plants]	Standard volume	3.77E-02	Nm3
OCE: platform, crude oil, offshore [Appropriation]	Number of pieces	4.14E-11	pcs.
RER: pipeline, crude oil, onshore [Appropriation]	Length	6.93E-06	m
RER: transport, freight, rail [Railway]	Kilometres (tkm)	1.26E-06	tkm
RER: transport, lorry >16t, fleet average [Street]	Kilometer (tkm)	3.63E-05	tkm
Outputs	**Quantity**	**Amount**	
NG: crude oil, at production [Appropriation]	Mass	0.997986	kg
Absorbable organic halogen compounds (AOX) [Analytical measures to fresh water]	Mass	6.57E-10	kg
Biological oxygen demand (BOD) [Analytical measures to fresh water]	Mass	0.000201	kg
Chemical oxygen demand (COD) [Analytical measures to fresh water]	Mass	0.000201	kg
Halon (1301) [Halogenated organic emissions to air]	Mass	5.80E-08	kg
Nitrogen [Inorganic emissions to fresh water]	Mass	4.92E-08	kg
Oil (unspecified) [Hydrocarbons to fresh water]	Mass	6.37E-05	kg
Sulphur [Inorganic emissions to fresh water]	Mass	1.71E-07	kg
Total dissolved organic bonded carbon [Analytical measures to fresh water]	Mass	5.51E-05	kg
Total organic bonded carbon [Analytical measures to fresh water]	Mass	5.51E-05	kg

HDPE Polyethylene granulate produced at plant			
Inputs	**Quantity**	**Amount**	**unit**
CH: disposal, average incineration residue, 0% water, to residual material landfill [residual material landfill facility]	Mass	0.01108	kg
CH: disposal, hazardous waste, 25% water, to hazardous waste incineration [hazardous waste incineration]	Mass	0.005476	kg
CH: disposal, municipal solid waste, 22.9% water, to municipal incineration [municipal incineration]	Mass	0.002991	kg
CH: disposal, plastics, mixture, 15.3% water, to municipal incineration [municipal incineration]	Mass	0.000697	kg
CH: disposal, wood untreated, 20% water, to municipal incineration [municipal incineration]	Mass	4.85E-08	kg
GLO: disposal, spoil from coal mining, in surface landfill [others]	Mass	0.021989	kg
GLO: disposal, tailings from hard coal milling, in impoundment [others]	Mass	6.83E-05	kg
NG: crude oil, at production [Appropriation]	Mass	0.997986	kg
RER: disposal, facilities, chemical production [building demolition]	Mass	6.96E-10	kg
RER: transport, lorry >16t, fleet average [Street]	Kilometer (tkm)	0.132714	tkm
UCTE: electricity, low voltage, production UCTE, at grid [production mix]	Energy (net calorific value)	4.366787	MJ
Outputs	**Quantity**	**Amount**	
RER: polyethylene, HDPE, granulate, at plant [polymers]	Mass	1.1	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	24.6334	MJ
Polyethylene Fleece Produced at Plant			
Inputs	**Quantity**	**Amount**	**unit**
CH: cement, unspecified, at plant [Binder]	Mass	0.0007	kg
CH: disposal, polyethylene, 0.4% water, to municipal incineration [municipal incineration]	Mass	0.1	kg
GLO: chemicals organic, at plant [organics]	Mass	0.0055	kg
RER: chemical plant, organics [organics]	Number of pieces	4.00E-10	pcs.
RER: core board, at plant [packaging papers]	Mass	0.024	kg
RER: heat, natural gas, at industrial furnace >100kW [heating systems]	Energy (net calorific value)	2.23	MJ
RER: packaging film, LDPE, at plant [processing]	Mass	0.023	kg
RER: polyethylene, HDPE, granulate, at plant [polymers]	Mass	1.1	kg
RER: transport, lorry >16t, fleet average [Street]	Kilometer (tkm)	0.145	tkm
UCTE: Electricity, medium voltage, production UCTE, at grid [production mix]	Energy (net calorific value)	0.863993	MJ

Water [Water]	Mass	24	kg
Outputs	**Quantity**	**Amount**	
RER: fleece, polyethylene, at plant [polymers]	Mass	1	kg
Alkane (unspecified) [Group NMVOC to air]	Mass	0.000275	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	0.864	MJ
PET Fabric Production			
Inputs	**Quantity**	**Amount**	**unit**
CN: electricity, low voltage, at grid [supply mix]	Energy (net calorific value)	25.47988	MJ
GLO: yarn, PET, at plant [Beneficiation]	Mass	1	kg
OCE: transport, transoceanic freight ship [Water]	Kilometres (tkm)	4.8	tkm
RER: electricity, low voltage, production RER, at grid [production mix]	Energy (net calorific value)	10.91979	MJ
RER: fleece, polyethylene, at plant [polymers]	Mass	1	kg
RER: packaging box production unit [cardboard & corrugated board]	Number of pieces	1.00E-09	pcs.
RER: transport, lorry 16-32t, EURO3 [Street]	Kilometres (tkm)	0.35	tkm
Outputs	**Quantity**	**Amount**	
Waste heat [Other emissions to air]	Energy (net calorific value)	36.4	MJ
Fabric Sample [Textiles]	Mass	0.25	kg
PET Fabric Laundry Cycle			
Inputs	**Quantity**	**Amount**	**unit**
CH: electricity, consumer mix [supply mix]	Energy (net calorific value)	1080	MJ
Detergent [Operating materials]	Mass	2.25	kg
Fabric Sample [Textiles]	Mass	0.25	kg
RER: tap water, at user [Appropriation]	Mass	3450	kg

Appendix 17: Inventory analysis for the 'cradle to laundry use phase of 0.25kg of cotton fabric from the raw material production, through yarn production, textile weaving plant to its experimental laundry use life cycle of 10 wash cycles.

Cotton fibres, at farm			
Inputs	**Quantity**	**amount**	**unit**
application of plant protection products, by field sprayer [work processes]	Area	69.98138	sqm
baling [work processes]	Number of pieces	0.00606	pcs.
combine harvesting [work processes]	Area	4.55173	sqm
fertilising, by broadcaster [work processes]	Area	15.15418	sqm
grain drying, high temperature [work processes]	Mass	0.089006	kg
mulching [work processes]	Area	5.051244	sqm
irrigating [work processes]	Volume	0.659706	m3
sowing [work processes]	Area	5.051244	sqm
tillage, harrowing, by spring tine harrow [work processes]	Area	20.20542	sqm
pesticide unspecified, at regional storehouse [Pesticide]	Mass	0.000306	kg
ammonia, liquid, at regional storehouse [inorganics]	Mass	0.025154	kg
ammonium nitrate, as N, at regional storehouse [mineral fertiliser]	Mass	0.012015	kg
di-ammonium phosphate, as N, at regional storehouse [mineral fertiliser]	Mass	0.011055	kg
di-ammonium phosphate, as P2O5, at regional storehouse [mineral fertiliser]	Mass	0.028252	kg
potassium chloride, as K2O, at regional storehouse [mineral fertiliser]	Mass	0.045127	kg
transport, lorry >16t, fleet average [Street]	Ecoinvent quantity ton kilometre (tkm)	0.014818	tkm
urea, as N, at regional storehouse [organics]	Mass	0.0087	kg
cotton seed, at regional storehouse [seed]	Mass	0.00736	kg
Outputs	**Quantity**	**Amount**	
cotton fibres, at farm [plant production]	Mass	0.4488	kg
Cotton yarn, at plant			
Inputs	**Quantity**	**amount**	**unit**
electricity, low voltage, at grid [supply mix]	Energy (net calorific value)	18.72705	MJ
packaging box production unit [cardboard & corrugated board]	Number of pieces	1.02E-09	pcs.
transport, lorry 16-32t, EURO3 [Street]	Ecoinvent quantity ton kilometre (tkm)	0.459	tkm
electricity, low voltage, at grid [supply mix]	Energy (net calorific value)	12.4847	MJ
disposal, paper, 11.2% water, to sanitary landfill [sanitary landfill facility]	Mass	0.102	kg

cotton fibres grinned, at farm [plant production]	Mass	0.6732	kg
cotton fibres, at farm [plant production]	Mass	0.4488	kg
Outputs	**Quantity**	**Amount**	
yarn production, cotton fibres [Benefication]	Mass	1.02	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	31.212	MJ
Textile, woven cotton, at plant			
Inputs	**Quantity**	**amount**	**unit**
disposal, paper, 11.2% water, to sanitary landfill [sanitary landfill facility]	Mass	0.02	kg
yarn, cotton, at plant [Benefication]	Mass	1.02	kg
transport, lorry 16-32t, EURO3 [Street]	Ecoinvent quantity ton kilometre (tkm)	0.35	tkm
packaging box production unit [cardboard & corrugated board]	Number of pieces	1.00E-09	pcs.
electricity, low voltage, production RER, at grid [production mix]	Energy (net calorific value)	10.91979	MJ
transport, transoceanic freight ship [Water]	Ecoinvent quantity tonne kilometre (tkm)	4.8	tkm
electricity, low voltage, at grid [supply mix]	Energy (net calorific value)	25.47988	MJ
Outputs	**Quantity**	**Amount**	
Fabric Sample [Textiles]	Mass	0.25	kg
Waste heat [Other emissions to air]	Energy (net calorific value)	36.4	MJ